17

Surface Finishing Technology Selection and Work Team Development Study in a Product Conversion

by

John Michael Eustis

B.S., Materials Engineering
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Submitted to the MIT Sloan School of Management
and the Department of Materials Science & Engineering
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Abstract

Intense research efforts have been undertaken in the past decade to try to understand what changes are necessary for U.S. companies to regain their competitive edge. Intelligent use of new technologies and implementation of high-performance work systems are just two of the many recommendations that have come out of these research efforts. This thesis is the result of a six and a half month study of both of these issues at one particular U.S. manufacturing company.

In an effort to reduce the production costs of surgical instruments, an investigation of automated surface finishing technologies was performed using a structured methodology. Several different technologies were researched including robotic finishing, several forms of mass finishing, and electrochemical finishing. Once the feasible technologies were identified, technical cost models were developed for each alternative and recommendations for capital expenditure were made. Several technologies proved to be attractive and would provide substantial cost savings compared with manual finishing.

Concurrently, a work team development study was performed in one individual production cell. The study included a workplace analysis of the production cell and the initial stages of work redesign based on the small business team (SBT) job model conceived by Janice Klein (1993). The SBT model is a form of self-managed work team based, in part, on sociotechnical systems theory. Commitment at all levels of the organization and an understanding of the corporate culture were identified as critical success factors for a work design project. Although work team development can be a lengthy process, substantial improvements in productivity can be achieved by implementing high performance work systems such as SBT's.

Thesis Supervisors:

Stuart B. Brown, Richard P. Simmons Associate Professor of Materials Manufacturing
Janice A. Klein, Visiting Associate Professor of Management Science

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I would like to thank all of the people at Codman & Shurtleff who helped me during the internship. A special thanks to Chris Sullivan, Jose Almeida, and the rest of the staff in New Bedford who provided me with an opportunity to experience the turbulent and exciting world of manufacturing and expanded my knowledge of Portuguese food and culture.

I would like to thank my thesis advisors, Janice Klein and Stuart Brown, for their wisdom and encouragement which enabled me to satisfy the multiple customers of this research.

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Table of Contents

Chapter One
Introduction

Many studies have been written about the steady erosion of U.S. manufacturing competitiveness since the end of World War II. Couple this with the rise of many new fierce competitors in many different nations and you might say that U.S. manufacturing companies are facing a crisis. If the U.S. is to become a world-class manufacturing nation, companies must be able to produce in small lots, customizing products to increasing demands. Intense research efforts have been undertaken in the past decade to try to understand what changes are necessary for U.S. companies to regain their competitive edge. Intelligent use of new technologies and implementation of high-performance work systems are just two of the many recommendations that have come out of these research efforts. This thesis is the result of a six and a half month study of both of these issues at one particular U.S. manufacturing company.

This thesis is essentially written in two separate pieces. Chapters Two through Five are devoted to a discussion of automated surface finishing technology selection and Chapters Six through Nine document a work team development study. The remainder of the introduction is dedicated to a description of the plant environment and the specific motivation for each project.

Description of the plant environment

My research for this thesis was conducted at Codman & Shurtleff, Inc., which is a member of the Johnson & Johnson family of companies. Codman employs about 800 people and has annual sales of over $100 million. Codman's primary business is neurosurgical instrumentation, although the company is currently branching into surgical monitoring systems. I performed my internship at Codman's largest manufacturing facility located in New Bedford, Massachusetts.

The New Bedford plant manufactures several thousand different products made primarily out of stainless steel and titanium. The plant could be classified essentially as a large "job shop." It manufactures small production batches of a large variety of products. Annual production of any one product code can range from as low as 25 units/year up to 4,000-5,000 units/year. The plant is divided into departments based primarily on product families. These departments are:

- Forge shop
- General machine
- General bench
- Boxlock
- Scissors
- Rongeurs
- Perforators

The forge shop produces the rough forgings for most of the products. The general machine department consists of an assortment of CNC machining centers which machine a wide variety of parts. General bench is an assembly and polish department for all of the low volume instruments, including the titanium instruments. Boxlock manufactures a large family of products that all have a boxlock joint design. Scissors, rongeurs, and perforators are departments dedicated to each specific product family.

The plant contains a wide variety of technologies. State-of-the-art CNC machining centers are located right next to 30-year-old grinding machines and finishing lathes. The majority of the products manufactured in New Bedford are still manually shaped and final polished. Most of the technology improvements that have been made in the last ten years have been in machining equipment. Relatively little investment has been made in finishing technologies.

The work force at the plant is somewhat different than one would expect to find in the New England area. The majority of the hourly associates at the New Bedford plant are first or second generation Portuguese-Americans. While most of the hourly associates speak English reasonably well, many of them cannot read and write English above the sixth-grade level.

Motivation for automated surface finishing technology investigation

Although Codman is still a leader in the field of surgical instrumentation, it faces tough competition from overseas manufacturers who can produce instruments at lower cost. The overseas manufacturers have been able to produce high quality instruments at lower cost due, in large part, to the difference in labor costs. A major component of the cost of a surgical instrument is the labor required for manual finishing. It is very expensive to hand-finish instruments in the U.S., given the high standard of living relative to competitor nations.

Manual polishing and buffing have other drawbacks besides cost. Quite often, each piece must be individually handled and worked, leading to non-uniformity problems and unacceptable reject/rework rates. Additionally some recent studies have shown that those engaged in this type of work are at high risk for developing carpal tunnel or repetitive motion syndrome, a potential workmen's compensation morass that many companies are understandably anxious to avoid.

All of these considerations pose serious production and quality control problems for manufacturers who are dependent on manual finishing processes to develop their final finish. Thus it is imperative that Codman investigate and invest in automated surface finishing technologies. There are numerous technologies available, both old and new, that would improve the performance, quality and cost of operations at Codman. Chapters Two through Five present the results of my investigation into several automated surface finishing technologies and their feasibility for implementation at Codman's New Bedford facility. Chapter Two contains a description of the methodology used for technology investigation and selection. A technical description of each finishing technology is presented in Chapter Three, followed by technical cost modeling analyses for each technology in Chapter Four. Finally, a set of detailed recommendations for capital investment are presented in Chapter Five.

Motivation for work team development study

Codman had been contract manufacturing all of its rongeurs in Germany for the past several years. In an effort to bring production hours back into the New Bedford facility, management decided to invest in new machining equipment and began producing rongeurs in New Bedford in early 1993. The rongeur cell was initially established with two people, a machinist and an assembler/polisher. As production ramps up, more people will be added to the rongeur cell. Codman's New Bedford plant currently operates without any team structures on the factory floor and plant management has realized that significant gains in quality and productivity could be achieved by introducing teams.

Management decided that the rongeur production cell would be an appropriate place to start a detailed team development study for several reasons. First, the rongeur cell was attractive for team development because it was new and had no established rules and norms that would have to be changed. Additionally, the new technologies used in rongeur production required different skills than other departments and would thus require a new work structure. Finally, the rongeur cell is relatively simple with a small number of different product codes which would make an initial attempt at redesigning the work more likely to be successful.

Many researchers have written about the inherent advantages of team-based work environments. A review of the evolution of work design leading to the current emphasis on teams will be presented in Chapter Six. Chapter Seven provides a detailed description of the methodology used in the rongeur cell while Chapter Eight tells the story of what actually happened in the rongeur cell. Chapter Nine presents the conclusions drawn from this case study and conclusions about the small business team job model utilized in the study.

Chapter Two
Technology Selection Methodology

Given the numerous technology choices available to the modern engineer, it is always appropriate to follow a structured methodology when conducting a technology feasibility study. The investigation of automated surface finishing technologies for Codman's surgical instruments was performed using a logical step-by-step approach. This chapter summarizes the major steps taken during this investigation. While the specific steps and worksheets described in this chapter are designed for investigating finishing technologies, the general framework can be used for other technology investigations. The major steps used to investigate finishing technologies are shown in Figure 2.1. Each of the eight steps will be discussed separately in more detail.

Step 1 - Create a master project schedule.

While most people understand the need to create a master schedule, this step is perhaps the most frequently overlooked part of any engineering project. Even when a schedule is generated, it is usually vague and incomplete and little thought is put into selecting the task durations and milestone dates. It cannot be overstated how crucial this step is to the overall success of a project. The project schedule should include every task that needs to be performed in order to complete the project, not simply the general project phases. An initial estimate of the duration for each task, usually in days, should also be included. If for no other reason, this will force the engineer to think about all of the tasks that must be accomplished and thus allow him to produce a realistic estimate of the time required to complete the project.

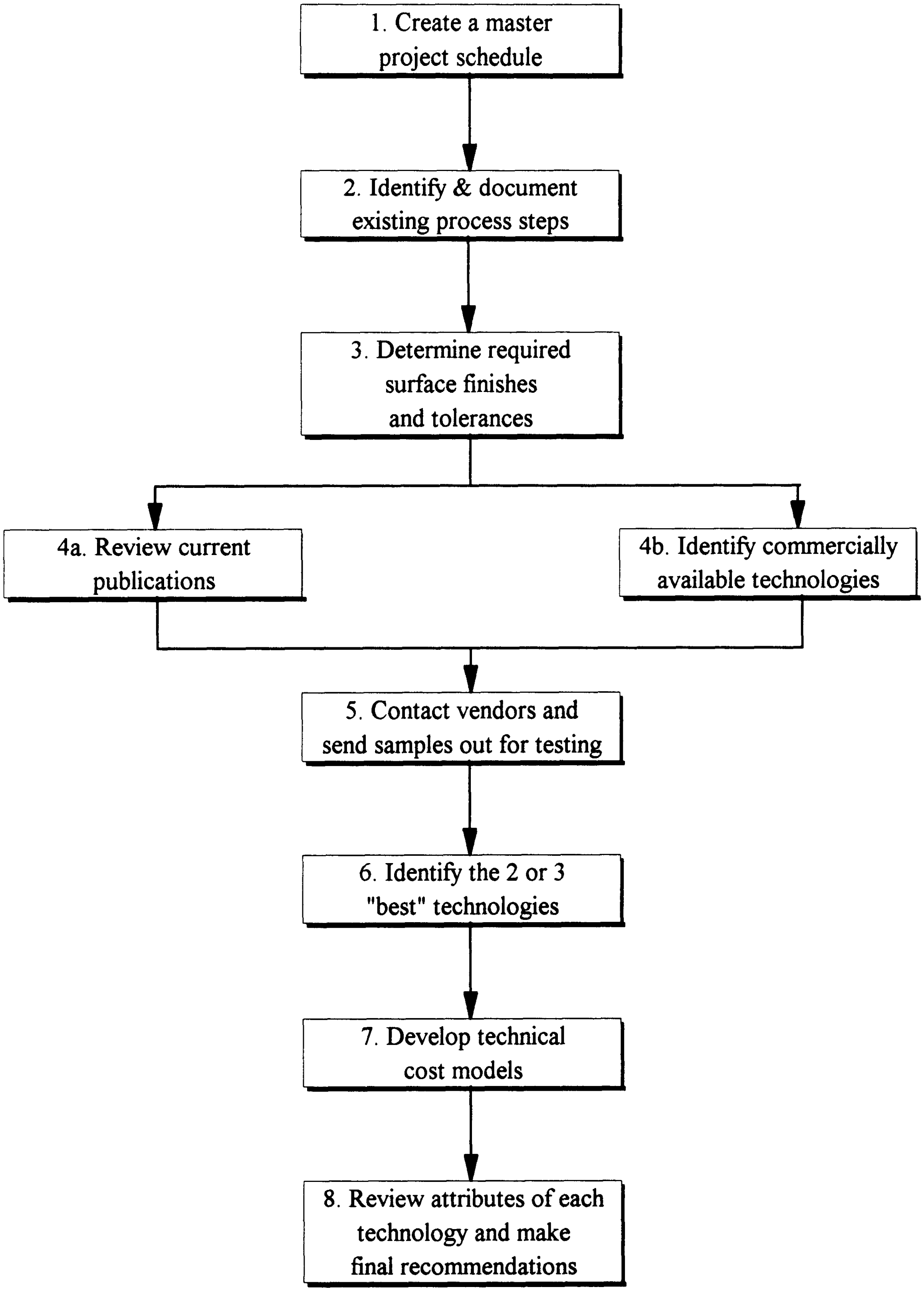


Figure 2.1 -Surface finishing technology selection methodology

There are many different ways to design and update a project schedule. I will suggest one approach here with the understanding that each individual may have their own preferred style. A simple spreadsheet, shown in Figure 2.2, can be created to delineate the tasks in a project. This spreadsheet contains project tasks, task durations, milestone finish dates for each phase, and percentage complete for each task. The individual project tasks are grouped into project phases and each phase has a milestone finish date. Since most engineers work on several projects at the same time this schedule allows the user to determine only the milestone dates with the knowledge that he will be working on other projects concurrently. Scheduling individual tasks for specific dates can be very time consuming and does not allow for the myriad of interruptions and unscheduled duties that the typical engineer must handle. Updating the '% complete' column once a week should give the user ample warning if the milestone date for a particular phase needs to be adjusted.

Sophisticated scheduling of multiple projects or detailed tracking of lengthy projects can be accomplished using specialized project planning software such as Microsoft Project. Regardless of the planning technique, it is important to take the time up front to develop a detailed schedule with realistic expectations for completion and to continuously update the schedule as the project progresses.

Step 2 - Identify and document the existing process steps.

Before an investigation of new finishing technologies can begin, a detailed understanding of the current finishing processes must be obtained and documented. Knowledge of every detail of the finishing process is important in order to identify opportunities to introduce automated finishing technologies. Each step in the finishing process should be documented along with all of the technical parameters associated with each step. For example, if a polisher manually shapes an instrument with a grinding belt it

Automated Surface Finishing Feasibility Study

Last updated on: 11/17/93

Project Task	*Duration*	*Scheduled Finish*	*% Complete*
Examine current grinding techniques		**Sept. 15, 1993**	**100%**
Identify the current grinding steps and equipment	2d		100%
Videotape each grinding step	3d		100%
Measure current grinding cycle times	3d		100%
Determine which steps are suitable for automation	2d		100%
Determine required surface finishes and tolerances	2d		100%
Determine processes to achieve required finishes & sha	5d		100%
Determine optimal level of automation flexibility	2d		100%
Review current publications	5d	**Oct. 15, 1993**	**100%**
Identify surface finishing technologies		**Nov. 1, 1993**	**100%**
Identify processes available in house	0.5d		100%
Test samples in house	5d		100%
Contact commercial vendors	5d		100%
Gather information from each vendor	2d		100%
Send samples out for testing	3d		100%
Analyze results for each technology	4d		100%
Identify the best 2 or 3 technologies	1d	**Nov. 1, 1993**	**100%**
Develop a technical cost model		**Dec. 1, 1993**	**75%**
Determine cycle times and cost for each vendor	7d		75%
Determine all other costs for each technology	7d		75%
Make a final recommendation	4d	**Dec. 15, 1993**	**10%**

Figure 2.2 - Example of a master project schedule

is important to know what type, size and grit belt he uses as well as the size and shape of the contact wheel and RPM of the grinding machine. Visually documenting each step in the process with a video camera can also be very useful, particularly when trying to describe a manual polishing operation to a potential vendor.

Step 3 - Determine the required surface finishes and tolerances.

Once the current process steps are identified, the required surface finishes and tolerances must be determined. In the case of surgical instruments, the surface finish is essentially a cosmetic feature. Therefore, the engineer must understand what the customer wants for a surface finish and why it is important. The dimensional tolerances are also needed to determine which technologies are capable of maintaining finished parts within the allowable tolerances. Surface finishing vendors will often ask what is the required finish and the necessary tolerances so it is important to obtain all of this information *before* talking with vendors. Figure 2.3 contains a worksheet which neatly displays all of the technical information about the finishing processes for a particular product. This format puts all of the process information on one page which allows for easy referencing during a conversion with a vendor.

Step 4a - Review current publications.

Once all of the technical information about the existing process is gathered, the engineer should undertake a review of the current publications. A wealth of information about new and old finishing technologies can be obtained from industry trade journals such as <u>Metal Finishing</u> and <u>Products Finishing</u>. Additionally, the Society of Manufacturing Engineers (SME) often publishes technical papers which address automated finishing

Finishing Data Collection Worksheet

Product Line: IVD Rongeurs

Product Number: 53-1197

Date: Nov. 17, 1993

Engineer: John Eustis

Operation	Critical Dimensions	Dimension, Start	Dimension, Finish	Measuring Device	Cycle Time (Hrs/Piece)	Media Type	Media Size	Contact Wheel Size and Shape	Machine RPM	Finish Attained (RA)
Inside rings are machined	Ring thickness	TBD	TBD	Vernier calipers	TBD	4 axis CNC mill using TiN coated HSS ring cutter	med. or large radius tool	NA	800	NA
Outside rings, necks and inside shanks are polished	NA	NA	NA	NA	TBD	1 1/2" wide grinding belt (cut from a 2" wide belt)	220J grit	14" dia., 1 1/8" wide shaped to fit neck	3400	26-35 Ra
All components are deburred	NA	NA	NA	NA	0.07	hand file	NA	NA	NA	NA
Mating surfaces of crossbar and long ring are glass beaded after heat treat	NA	NA	NA	NA	NA	glass bead at 80 psi	MS - ML	NA	NA	matte finish
Outside rings, necks and inside shanks are compounded	NA	NA	NA	NA	0.05	Scotch-Brite EXL Deburring and Finishing Wheel	8S Fine	NA	1800	satin finish 13-16 Ra
Assembled instrument is shaped	Crossbar height	NA	NA	thickness gauge	0.083	2" wide grinding belt	120J grit	12" dia., 2" wide, Non-fray	3400	45 Ra
Entire instrument is polished	Tip width	TBD	nom. +-0.005"	gauge	0.058	2" wide grinding belt	220J grit	12" dia., 2" wide, Non-fray	3400	26-35 Ra
Entire instrument is compounded	Tip width	TBD	nom. +-0.005"	gauge	0.067	Norton Bear Tex Series 1000 Deburring Wheel	12x2x5	NA	1800	satin finish 13-16 Ra
Instrument is passivated	NA	NA	NA	NA	TBD		NA	NA	NA	satin finish 13-16 Ra

NA = not applicable
TBD = to be determined

Figure 2.3 - Example of a finishing data collection worksheet

technologies. Some textbooks, such as The Metals Handbook, may also provide information about well established technologies, although they may not be current enough to contain references to emerging new technologies. Many of these publications can be found in the sciences/engineering library of the local college or university, which is often open to the public. One or two days of research at the library can often yield substantial amounts of information. Engineers working in industry should not forget about the vast resources of information available at local colleges and universities.

Step 4b - Identify commercially available technologies.

As the engineer gathers information in publications, he should also seek out information from industry sources. The Thomas Register is perhaps the best source for identifying potential vendors of finishing technology. Talking with vendors who currently supply items to the company can also yield some useful information. While a particular vendor may not sell automated finishing equipment, he may know who to contact. The engineering and manufacturing staff at the company should also be consulted for information. Many of them have worked at other companies and may have experience with a particular technology or vendor.

At this point in the investigation it is important to keep an open mind and perform as broad a search as possible. The engineer should not think solely about using automated technology to replace one or more discrete steps in the current process. He should also continue to think of ways in which new technologies could completely change the finishing process.

Step 5 - Contact vendors and send samples out for testing.

Once a set of potential vendors has been identified, the engineer should begin sending samples out for testing. The objective is to gain as much information about the test processes as possible with a minimum number of test samples. Therefore several samples with varying initial finishes should be sent out to learn how much a particular process can refine the surface. Since dimensional changes are important, accurate measurements of the critical dimensions should be recorded before each sample is sent out for testing. Test sample dimensions can be stored on a worksheet as shown in Figure 2.4. The worksheet should leave space for the dimensions to be recorded when the samples are returned from the vendor.

When the vendor returns the samples be sure to obtain as much information as possible about how the samples were processed. Vendors are constantly testing samples for potential customers and if you don't get the processing information when the samples are returned they may not remember the exact processing conditions for your samples later on.

It is also very important to keep an accurate record of what samples were sent to each vendor, when they were sent, and when the vendor promised to return them. Figure 2.5 shows an example of a worksheet that can be used to track all of this testing information. The worksheet should be periodically updated by contacting each vendor and determining the status of the test samples. At least several months should be allocated for this testing process because vendors don't always give high priority to processing free samples. Frequent contact with each vendor will help ensure that they meet the promised due dates.

Test Sample Dimensional Worksheet

Product Line: **IVD Rongeurs**
Product Number: **53-1197, 1196**
Date: **Sept. 23, 1993**

Process: **Electropolishing**
Vendor: **Molectrics**
Engineer: **John Eustis**

Sample No.	Initial Finish	Tip Height Before	Tip Height After	Tip Width Before	Tip Width After	Ring Thickness Before	Ring Thickness After	Shank Thickness Before	Shank Thickness After
1	120 grit	0.23	0.224	0.096	0.094	0.091	0.088	0.204	0.202
2	120 grit	0.231	0.229	0.096	0.095	0.095	0.09	0.189	0.188
3	220 grit	0.231	0.225	0.095	0.094	0.086	0.081	0.188	0.187
SPEC.		**0.226**	**0.226**	**0.09**	**0.09**	**0.07**	**0.07**	**0.175**	**0.175**
TOL.		**+-0.008**	**+-0.008**	**+-0.005**	**+-0.005**	**min.**	**min.**	**min.**	**min.**

Sample No.	Final Finish	Tip Opening Before	Tip Opening After	Rings Width (Closed) Before	Rings Width (Closed) After	Rings Width (Open) Before	Rings Width (Open) After
1		0.529	0.532	3.021	3.01	3.969	3.985
2		0.49	0.495	3.047	3.035	3.931	3.935
3		0.608	0.62	3.001	2.993	4.001	4.029
SPEC.		**0.44**	**0.44**	**3.00**	**3.00**	**3.97**	**3.97**
TOL.		**min.**	**min.**	**+-0.10**	**+-0.10**	**Ref.**	**Ref.**

Figure 2.4 - Example of a test sample dimensional worksheet

Status of Finishing Technology Research as of : 12/14/93

Technology	Vendor	Samples Sent out	Scope of Work	Date Sent Out	Date Returned	Results Analyzed?
Robotic finishing	Bula	2 IVD Rongeurs: 1 @ satin finish 1 @ as-machined	shape crossbar and polish outside rings	8/19/93	11/15/93	yes
Centrifugal disc tumbling (wet)	RMS	4 IVD Rongeurs: 1 @ satin finish 3 @ 220 grit	Cut down and polish entire instrument	9/7/93	9/29/93	yes
Centrifugal barrel tumbling (dry)	PEGCO	3 scissors @ 100 grit 2 rongeurs @ 120 grit 1 satin finish rongeur	Cut down and polish entire instrument	9/29/93	10/12/93	yes
Burlytic process	Debur	9 IVD Rongeurs: 1 @ satin finish 2 @ 120 grit 5 @ 220 grit 1 @ as-machined	Polish entire instrument	8/25/93	9/28/93	yes
Electropolishing	Molectrics	6 IVD Rongeurs: 1 @ satin finish 2 @ 120 grit 2 @ 220 grit 2 @ tumbled	Polish entire instrument	8/24/93	9/20/93	yes

Figure 2.5 - Example of testing status worksheet

Step 6 - Identify the 2 or 3 "best" technologies.

Once the initial test samples have been received back from the vendors, it will become apparent that some processes do not produce acceptable finishes or are simply too costly. At this point, the engineer should begin to narrow his focus to those two or three technologies that are most promising. A half-day meeting of the engineering staff is recommended to present the results of the initial tests. Receiving input from a number of different people is important so as to eliminate individual biases toward one technology or another. The decisions should be based on a set of criteria that have been agreed upon by the staff. For example, at Codman the processing cost per part, flexibility to process different instruments, and process development time were considered the most important attributes. The result of this meeting should be a flowchart containing the most promising technologies and their potential applications. One segment of the chart developed at Codman is shown in Figure 2.6. A more detailed investigation of the chosen technologies will follow.

Step 7 - Develop technical cost models.

A more in-depth investigation of the most promising technologies begins by collecting the data to build technical cost models for each technology. Technical cost models, described in detail in Chapter Four, are spreadsheets designed to calculate the processing cost per part. Collecting cost information from a vendor provides the engineer with much greater insight into the technology than just processing costs. Information regarding processing time, equipment capacity, equipment cost, and setup times is necessary to build cost models but it also allows for technology comparisons based on criteria other than processing cost. Sensitivity analyses can also be performed thus enabling the user to determine the primary cost drivers for each technology.

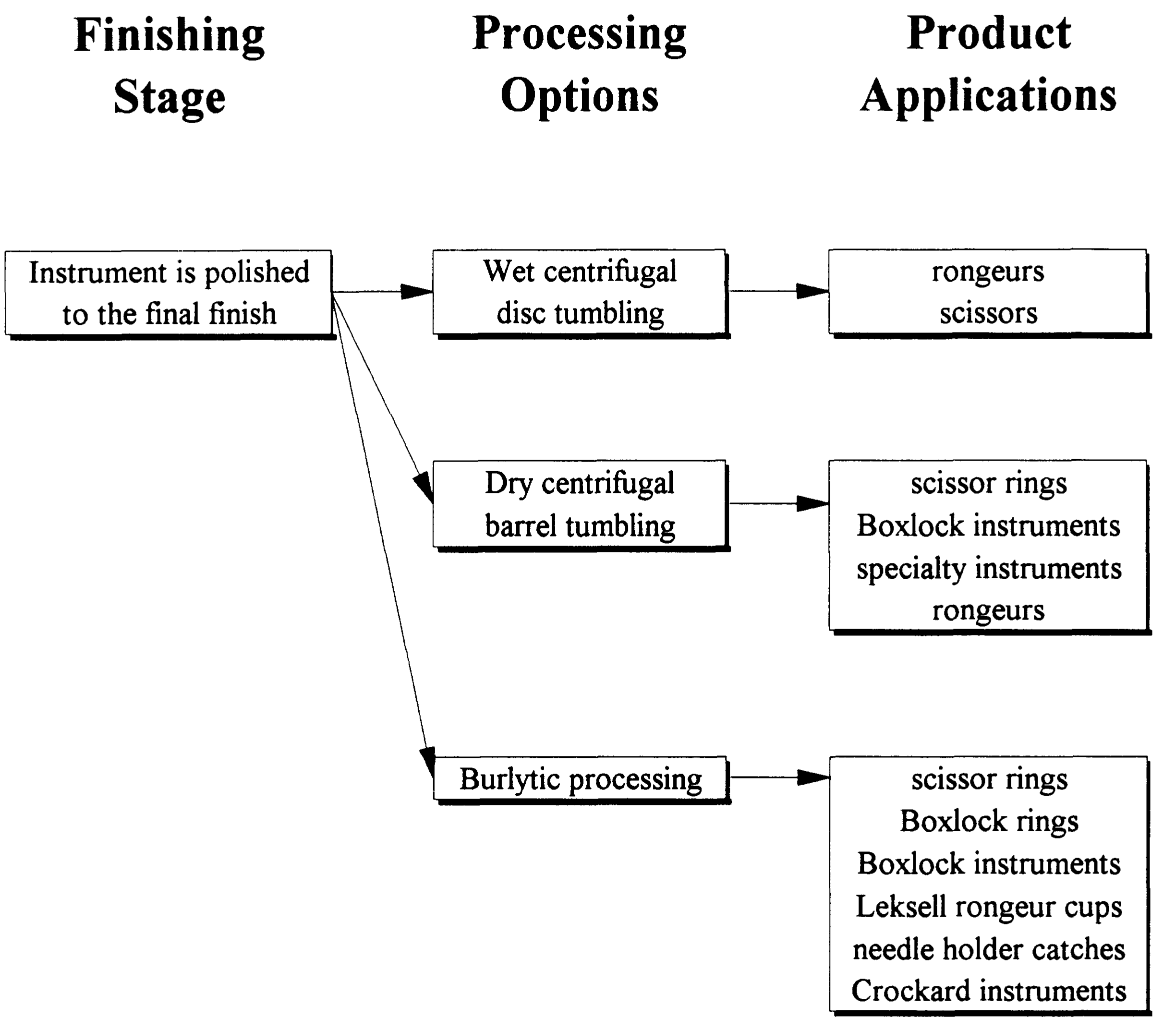


Figure 2.6 - Finishing technology flowchart

Step 8 - Review attributes of each technology and make final recommendations.

Once the technical cost modeling has been completed, the engineer should have a very good understanding of each technology and its capabilities. It is at this point that he should call another meeting of the engineering staff to discuss the results of the cost modeling and any additional sample testing. All of the technology attributes should be discussed at this meeting and comparisons made for each important criterion. The results of each technology investigation should be documented regardless of whether or not they have been chosen for implementation. Documented process technologies sitting on the shelf are an asset worth keeping. The conclusions and recommendations specific to Codman, presented in Chapter Five, are a good example of documentation of each technology investigated.

Final Thoughts

Whether one uses the methodology presented here or somewhere else, I think it is always crucial to create a detailed project schedule and document everything during the investigation. Creating a project schedule will force the engineer to adopt some form of structured methodology. Documentation is essential particularly since the modern-day engineer is constantly being pulled in different directions by different people and projects. When an engineer documents everything it frees up his mind to concentrate on the task at hand, thus making him more efficient and more thoughtful.

Technology investigation and selection are often very complex tasks requiring engineering and manufacturing expertise. I cannot stress how important it is to approach this type of project in a logical step-by-step manner. Even the most brilliant engineers can get lost in the huge volumes of information generated during a thorough investigation. A logical approach can help an engineer see the forest through the trees!

Chapter Three
Automated Surface Finishing Technologies

There are numerous technological choices in the area of surface finishing and the list continues to grow every year. The area of automated surface finishing is probably growing even faster. Currently, there are six broad classes of automated surface finishing technologies, as follows:

1. CNC machining
2. Robotic finishing
3. Mass finishing
4. Electrochemical finishing
5. Chemical finishing
6. Abrasive and nonabrasive blasting

The majority of automated finishing technologies can be placed in one of these six categories. Three of the six classes of technology are discussed in detail in this chapter: robotic finishing, mass finishing, and electrochemical finishing. A detailed explanation of each technology and its major technical issues is presented along with a listing of the advantages and disadvantages of each choice. The conclusions reached for each technology are presented in Chapter Five along with the specific recommendations for Codman.

Robotic Finishing

The field of robotic finishing is in its infancy, having been actively researched for only the last ten years. However, in this short period of time major technological advancements have been made and many robotic systems have been placed in production for deburring, finishing, and grinding applications.

Position Control

The most important issue in robotic finishing is how to control the action of the robot against the abrasive wheel or belt. Several control methods have been developed for use in robotic finishing systems. The first control method developed for robotic finishing was position control. The robot moves the part to a certain, predetermined position every time. This method is generally used with dimensionally stable abrasives such as coated abrasive belts or discs. The abrasive product changes dimensions very little during its lifetime, so the robot does not usually need to compensate for tooling wear. Applied force is not controlled by the robot, and care must be taken so that the applied forces do not stall the tool, exceed the cut rate of the abrasive, or overload the robot.

Accuracy of the grinding process depends on the consistency of the part being ground, and the repeatability and stiffness of the robot. (Graf, 1993) A high load capacity robot is generally desirable, as this allows higher applied forces, which can improve cycle times and extend abrasive life. However, when the magnitude of the applied forces is increased, a stiffer robot is required in order to maintain the accuracy of the grinding process.

Position control is not recommended for applications requiring close dimensional tolerances of less than ±0.020." (Graf, 1993) Position control is also not recommended when the parts have widely varying amounts of metal to remove. In such cases, the robot must be programmed for the worst part that may be encountered, and thus the robot will spend unnecessary time grinding on the parts which require less metal removal.

Force Control

Force control is a more recent development in robotic finishing. Force control methods allow the robot to accurately apply forces ranging from less than half a pound to 50 pounds or more. Force control is used when running low to medium compliance abrasives, such as coated abrasives for finishing and deburring, and Scotch-Brite non-woven abrasives.

Force control devices provide automatic compensation for product wear. They also compensate for part to part variations, allowing less accurate parts to be run without any changes in programming. Force control devices also greatly simplify programming, since they will compensate for any inaccuracies in robot position. A force control system will track surfaces that vary from the robot's path by one-fourth of an inch or more. This variation might be due to simpler programming, part to part variations, or fixturing accuracy. Simpler fixturing can often be used to reduce cost and complexity. Older, less repeatable robots may be used effectively, since position accuracy is not as critical.

Force control devices apply forces more consistently than an off-hand operation, which may allow the use of higher average forces. The improvement in force consistency, along with the robot's precision, often allows more aggressive products to be used. This often increases part processing speed two to five times over the equivalent manual operation. (Graf, 1993) The abrasive media will generally have increased life, since the robot controls force, position and speeds correctly.

A more detailed description of position control, force control, and the variety of force control devices can be found in the articles by Tim Graf (1993), Senior Methods Engineer at the 3M Robotics Lab.

The following sections present the advantages and disadvantages of robotic finishing, followed by a listing of vendors currently active in the robotic finishing market.

Advantages of Robotic Finishing

- very good repeatability of surface finish
- variable surface finish across the part is possible
- reduced usage of consumables
- reduced labor cost
- capability for on-line inspection

Disadvantages of Robotic Finishing

- difficult and expensive to fixture for a variety of instruments
- high to extremely high capital investment
- lengthy programming time for new parts
- ability to grind to critical tolerances can be difficult
- lengthy development period because no in-house expertise in robotics

Robotic Finishing Vendors

- BULA, Switzerland - MR250.0 Polishing Cell
  - fully enclosed, turn-key system
  - system does not use force control; the robot is programmed using position control
  - >$400,000 price tag is the most expensive on the market

- Hammond Machinery, Michigan - Yamaha Kappa-1 Polishing Robot
    - 3M Robotics Lab recommended working with Hammond on system development, Hammond's force-control grinding units are the best in the business
    - Hammond uses force control in its system designs and is the most experienced with force control devices

- Acme Manufacturing Co., Michigan - Robotic Finishing Cell
    - system is similar to BULA without an enclosure

- 3M Robotics Lab, Minnesota
    - 3M is not a robotics vendor but has a full research lab for robotic finishing

Mass Finishing

Mass finishing is a process in which mechanical means are used for deburring, radiusing edges and corners, improving microfinish, and removing oxides and scale from surfaces. (Tulinski, 1993) Parts are loaded into a container, normally with some abrasive media, water and compound. Action is applied to the container to cause media to rub against parts, or parts to rub against one another; so removing burrs, radiusing edges and refining surfaces.

Principal Advantages

Mass finishing offers a simple, inexpensive method of surface and edge finishing and refinement. Mass finishing eliminates time-consuming part handling and labor-intensive off-hand finishing. Mass finishing ensures consistent results from part to part and batch to batch. Mass finishing handles all types of metals and many nonmetallic materials in a variety of shapes and sizes. A wide range of finish requirements can be achieved.

Limitations

Mass finishing generally affects the entire part; that is, all edges, corners and surfaces exposed to the media. Usually, it is not possible to process one area of a part without special tooling or fixturing. Corners receive the greatest amount of action, whereas edges receive less action than corners but more than flat surfaces. Holes and recesses can be particularly difficult to process.

There are several basic mass finishing processes (Hignett, 1982), as follows:

- Tumble Barrel Finishing
- Vibratory Finishing
- Spindle Finishing
- Centrifugal Disc Finishing
- Centrifugal Barrel Finishing

There are several other, less common mass finishing processes such as reciprocal finishing, chemically accelerated vibratory and centrifugal barrel finishing, and electro-chemical accelerated mass finishing. These processes will not be discussed in detail because they are generally very expensive and designed for special applications.

A discussion of the underlying science of mass finishing will be presented first, followed by a description and analysis of each individual process.

The Mechanical Forces of Mass Finishing

Before selecting equipment, media and compound, an understanding of the nature and effect of forces applied within a load of parts and media is helpful. There are essentially two types of applied forces, compression and shear. (Zaki, 1992) During deburring and cut down operations with abrasive compounds and media, shear forces act on the part surfaces resulting in cutting and metal removal. (see Figure 3.1) Simultaneously, compressive forces act on the abrasive particles, causing the particles to break down into finer sizes.

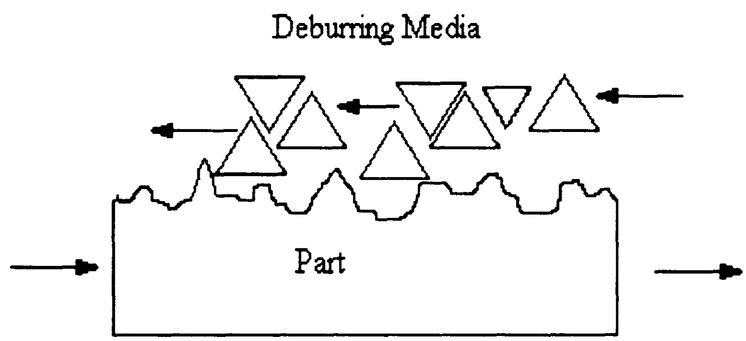


Figure 3.1 - The effect of shear forces on the part surface during deburring.

In burnishing operations, with nonabrasive media, the predominant force in action is that of compression. The applied compressive load from the media is transferred to the surface of the parts at points of contact with the media. Under this compressive stress, the relatively malleable metal layers on the surface are plastically deformed and spread out to smooth out the "peaks and valleys" on the surface. (see Figure 3.2)

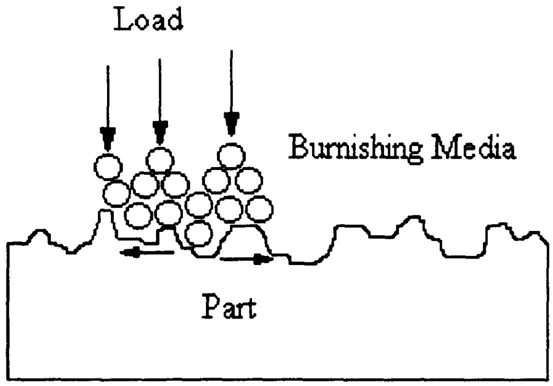


Figure 3.2 - The effect of compressive forces on the part surface during burnishing.

The ductility of the metal being processed must also be taken into consideration when choosing the parameters for mass finishing. The metal surface layers may work harden as they deform under the compressive loads transferred by the media. As the metal work hardens, the amount of additional surface refinement will decrease if the media load remains unchanged. The surface roughness of metal parts that have low initial ductility will only be reduced slightly during burnishing operations because the surface metal will work harden quickly preventing further refinement.

Mass Finishing Media Types

Media used in mass finishing are selected to achieve: (1) separation between parts during processing and thereby prevent part damage; and (2) provide the required surface finish, e.g., deburring, smoothing, or burnishing. (Zaki, 1992) Media selection can critically affect the outcome of any mass finishing process. The selection process is often complicated by the fact that there are a myriad of media types, shapes, and sizes available. Materials commonly used for media include:

- manufactured preform abrasives (bonded with plastic or ceramic matrices)
- metals - hardened steel, stainless steel
- natural agricultural products - ground corncob, ground walnut shells, sawdust
- natural stones and minerals - limestone, granite, corundum

Abrasive type media, usually in ceramic or plastic preforms, are available to satisfy various degrees of metal removal. The higher the abrasive content of the media, the faster the cut rate. Fast cutting media usually leave the parts with a matte finish, while slow cutting media can be used for smoothing surfaces to a lower microinch finish. The abrasive media utilize shear forces against the part surfaces to achieve metal removal. Generally, ceramic preforms are more aggressive and wear at a slower rate than plastic preforms. Some plastic formulations may require significant waste water treatment before discharge and can solidify in and clog up waste water piping.

Nonabrasive media are primarily used for burnishing with no stock removal. These media rely primarily on compressive forces acting against the part surfaces to achieve surface refinement.

Media Shape and Size

Media shape is also an important factor in any mass finishing process development. Maximum deburring and cut down efficiency is obtained with flat-sided media shapes, such as triangles, pyramids, and star shapes, due to the larger surface contact that these shapes offer. Triangular shapes give greater action on part surfaces relative to edges and corners. Triangles are the most standard preformed media because they keep their shape during the useful life and they reach into corners well.

Cylinders, cones, and spheres roll over surfaces for greater action on edges and corners. Precision or less aggressive stock removal is usually obtained with cylinders and cones, which offer a line contact to the part surface. Spherical media offer point contacts and are usually recommended for burnishing operations.

The media size should be chosen so that the material won't wedge into the work pieces. Media should flow freely through holes or be large enough not to pass through, in order to prevent media lodging. Generally, larger size media will have a faster abrasive action, due to the higher pressure exerted at points of contact with the parts. However, larger size media will cause greater variation between metal removal at edges, corners, and surfaces. Smaller size media will provide greater uniformity of metal removal.

Compound Selection

Once the finishing requirements and the media have been selected, an appropriate compound must be chosen. Compounds are designed to provide a certain degree of lubricity, water softening, and pH conditioning to produce a given effect on the part surface. Different compounds are designed for cleaning, deburring, burnishing, and rustproofing. Usually, the media supplier can recommend an appropriate compound and will often supply it as well. It should be noted that using plain water without compound in flow-through systems is counterproductive. In the absence of detergency, wetting of the media and parts is ineffective, and flushing of metallic fines and abrasive residues is incomplete. (Zaki, 1992) Likewise, excessive compound concentration can also reduce the efficiency of mass finishing processes.

Tumble Barrel Finishing

Barrel tumbling was the original mass finishing process, having been in use prior to the Iron Age. (Hignett, 1983) With the use of modern techniques and materials, barrel tumbling is capable of handling fragile and precision parts, achieving very fine and bright finishes. The initial equipment investment is low, as are the maintenance costs. However the process is invariably slow and requires a skilled operator to achieve high quality results. More modern mass finishing processes offer greater versatility and convenience, with better use of labor and more consistency of quality at higher production rates.

Vibratory Finishing

Modernization of the mass finishing industry began with the introduction of vibratory finishing equipment in the 1950's. (Tulinski, 1993) Vibratory finishing is currently the industry standard for mechanical surface finishing and there are numerous manufacturers of equipment, media, and compounds. Fully automated vibratory systems are available both for continuous flow and flexible manufacturing applications.

A vibratory finishing machine is normally an open-ended tub or bowl-type vessel mounted on springs. The bowl or vessel is usually lined with a polyurethane material. Vibratory action is created either by a vibratory motor attached to the bottom of the container, by a shaft with eccentric weights driven by a standard motor, or by a system of electromagnets operating at 50 or 60 Hz. The resulting action is tapping or rubbing of media against the parts.

Vibratory equipment has the capability to handle large or small parts and is usually very economical to operate and maintain. Vibratory finishing is typically the process of choice when the required process times are less than a couple of hours. However high quality, bright surface finishes cannot be achieved with vibratory finishing equipment because of the tapping action of media against parts. The tapping and rubbing action may also make vibratory finishing unsuitable for processing of high-precision or fragile parts.

High Energy Finishing Processes

High energy mass finishing is a process where the energy created within the mass in a container is greater than standard vibratory processing. (Hignett, 1983) Initially, high energy mass finishing was developed to achieve shorter process cycles. Additionally, high energy processes use the energy more efficiently and are usually easier to control. Some high energy systems have variable energy levels which gives those systems the flexibility to perform aggressive stock removal at high energy levels as well as more gentle smoothing of edges and corners at lower energy levels.

Spindle Finishing

This process is used primarily when part-on-part impingement is not acceptable. The parts are fixtured, mounted on rotary spindles, and are immersed in a circular rotating tub that is filled with loose abrasive media, water, and compound. Dry media can also be used for high luster applications. Media flows around the parts as the parts are slowly rotated or articulated on the spindles, causing refinement of edges and surfaces. Masking and proper fixturing, along with angle of presentation of the spindle, allow this to be the only form of mass finishing in which selective deburring and finishing can be achieved. (Tulinski, 1993)

Spindle machines are very efficient and generally offer the fastest process cycles. The process is easily automated with pick-in-place units and robotics for part loading and unloading. The major drawback is that fixturing can be very expensive, particularly when there is a wide variety of parts to be processed. Since the fixtures are also exposed to the media they will wear out over time resulting in frequent replacement costs. This process is ideal for uniform shaped parts such as gears, sprockets, and bearing cages where fixturing is simple and action of the abrasive will be uniform over all significant edges and surfaces.

Centrifugal Disc Finishing

The centrifugal disc process is the newest form of high energy mass finishing. The machine consists of an open container with stationary side walls. The bottom of the container is formed by a disc which rotates at relatively high speed. The container is loaded with parts and media and as the disc rotates, the mass inside the container is accelerated outward and upward by the centrifugal force of the disc rotation. The stationary side wall acts as a brake, slowing down the moving action of the mass. The parts and media rise to the top of the load and then flow inwards towards the center of the disc where they are accelerated again. (see Figure 3.3)

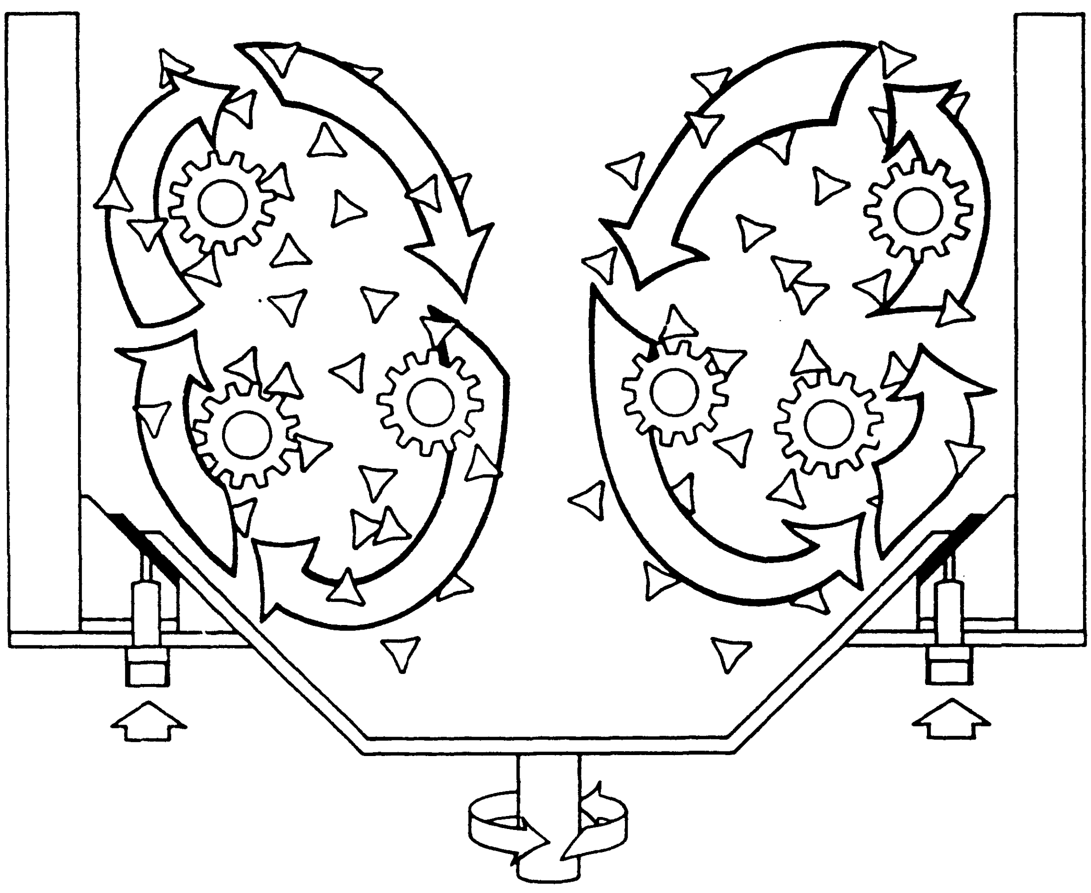


Figure 3.3 - Centrifugal Disc Finishing

Typically, the centrifugal forces generated are between three and seven times the force of gravity. (Tulinski, 1993) As a result, the process cycles are up to one twentieth of those of vibratory processing. The short process cycle results in reduced floor space requirements, increased versatility, and less work in progress. Like vibratory equipment, parts can readily be inspected during the process cycle, and variable speed can, on occasions, combine deburring with a more gentle surface refinement operation.

Centrifugal disc machines are not suitable for very small parts or fine media because the parts or media might lodge in the gap between the disc and the side walls. Usually, a different machine is required to process parts dry. Semi-automated and fully automated centrifugal disc machines are readily available.

While centrifugal disc machines have been on the market for the past 20 years, until recently their use had been limited due to troublesome, and therefore expensive, maintenance. Manufacturers had difficulty maintaining a uniform and small gap between the spinning disc and the stationary side walls. In the last ten years, changes have been made in the materials and designs of centrifugal disc machines to improve their reliability. Hard, wear resistant ferrous materials, lined with hot-poured, ultra wear resistant polyurethane are now used for the disc and the stationary side walls. Up-flow compound and lubrication systems have also been developed which eliminate the possibility of fine media and metallic fines resting in the gap and abrading either the side walls or the disc. These improvements in reliability have made centrifugal disc finishing commonplace in industry.

Centrifugal Barrel Finishing

Centrifugal barrel equipment consists of a number of containers or drums mounted on the periphery of a turret. The turret rotates at high speed in one direction while the drums rotate at a slower speed in the opposite direction. The drums are loaded with parts, media, compound and sometimes water. The turret rotation creates a high centrifugal force up to 50 times the force of gravity. (Tulinski, 1993)

These high forces totally compact the mass within the drums. The counter rotation of the drums generates a friction coefficient between the mass and the drum wall; in this phase, parts and media "climb a hill." At the apex of this climb, the gravitational force extended outward overcomes the mass/drum wall friction coefficient, causing the parts and media to go through a slide. The mass sliding outward rubs against the climbing mass approaching the drum apex. (see Figure 3.4) This sliding action removes burrs, generates radii, and refines all edges and surfaces.

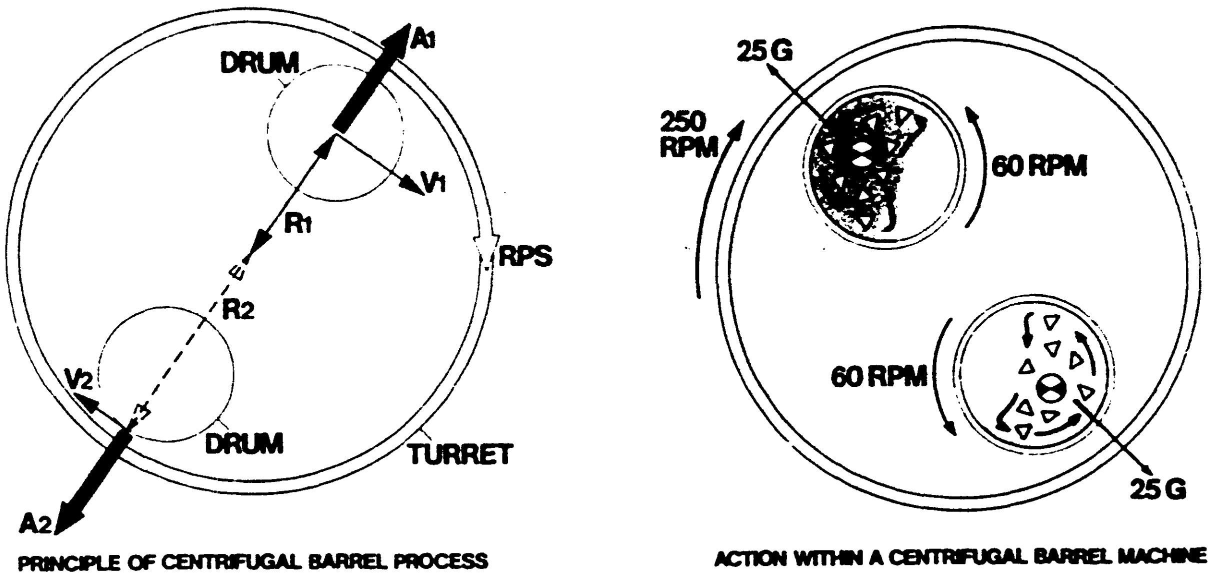


Figure 3.4 - Centrifugal Barrel Finishing

Centrifugal barrel finishing achieves very short process times, generally less than one fiftieth of the time taken in vibratory equipment. The smooth sliding action of media against parts produces consistent results and very high tolerances can be maintained even with fragile parts. High surface finishes are obtainable because the centrifugal barrel process is also the gentlest, using a pure rubbing action. The centrifugal barrel process offers the flexibility to process parts wet or dry without major setups or separate machines.

An additional advantage of the process is its ability to impart high compressive stresses on the surface of the parts, which can increase the fatigue resistance of the finished part. (Hignett, 1982) The improved fatigue strength is generally greater than that which can be achieved by any other finishing processes combined with shot peening, and almost always at significantly lower cost.

One limitation of centrifugal barrel finishing is that it does not allow for in-process inspection since it is a closed process. Loading and unloading of a centrifugal barrel machine is more labor intensive than for other mass finishing equipment, particularly when performing wet processing. Automated batch processing is possible but is difficult to achieve and is relatively expensive.

Mass Finishing Equipment Selection

It is difficult to recommend a specific procedure for selecting mass finishing equipment because each application is unique and requires individual consideration. However, a set of general guidelines has been developed by John Kittredge (1987), an experienced mass finishing consultant. These guidelines, although very simple, should give the engineer a good starting point for his investigation. I have also included a selection criteria matrix immediately following the selection guidelines. This matrix provides the engineer with a detailed summary of the technical attributes of each process. Both of these tools, along with the technical cost models discussed later, should provide the engineer with enough information to focus his/her investigation on one or two optimal processes.

A Simplified Set of Guidelines for Selection of Mass Finishing Equipment

1. If your parts can be processed in a vibratory finishing machine in less than about 15 minutes and the volume of parts can justify it consider a continuous tub or continuous round vibrator.

2. If your parts can be satisfactorily processed in a vibrator in less than a few hours, then either a round vibrator or tub vibrator is recommended.

3. A round vibrator is suggested. If your part is too big for the number of parts produced each year or more than one type or size media is required, then a tub vibrator may be needed.

4. If either step 2 or 3 require more than a few hours in the vibratory machine, then a centrifugal disc or centrifugal barrel should be considered.

5. If the parts are too big for the centrifugal machines, then the round vibrator or the tub vibrator is reconsidered.

6. If very long cycles are required, then a centrifugal disc is considered or, if the parts are very critical or too big or too small, then a centrifugal barrel will be preferred.

7. If parts cannot be allowed to contact one another but otherwise process acceptably in step 2 or 3, then use fixtures or compartments in the vibratory machine.

8. If parts from step 7 require too much work, then consider either a spindle machine or a compartmented centrifugal barrel.

Mass Finishing Equipment
Selection Considerations

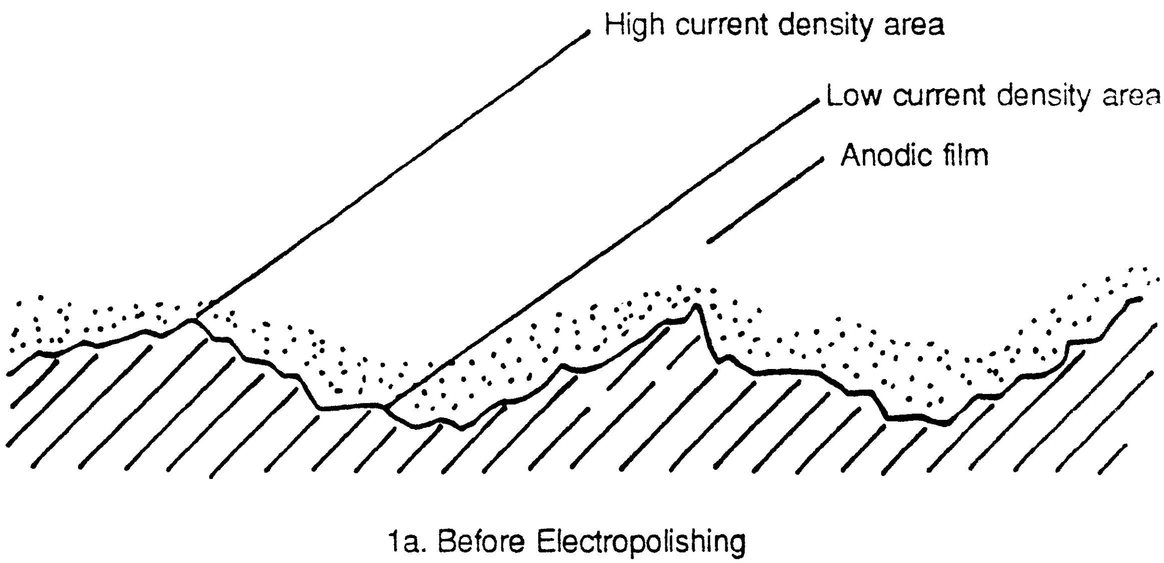
	Horizontal Barrel	Round Vibrator	Centrifugal Disk	Centrifugal Barrel	Spindle Finish
Time cycles	very long	medium	short	short	very short
Media wear **Media size**	slow large	moderate medium	very high small	high small	very high very small
Equipment cost	low	medium	very high	high	high
Typical kinds of processes	heavy radiusing, burnishing, dry polishing	deburring, smoothing, stock removal, burnishing	aggressive stock removal, smoothing, deburring	micro-finishing, polishing, fast stock removal	aggressive deburring, stock removal, NO impingement
Part size limitations	medium	restricted length by bowl diameter	part length severely restricted by chamber size	small to moderate, fixturing or compartments possible	some part geometry restriction
Type of energy	rotational, gravity slide	kinetic, vibratory	centrifugal, toroidal	centrifugal, pressure	spin, media resistance
Continuous or batch	batch	continuous possible	batch	batch	batch
Liquid compound usage	LOW	high with flo-thru systems	high with flo-thru systems	LOW	medium
Working capacity	50%	80-90%	30-40%	60% - wet 80-90% - dry	N/A fixtured
Exterior or interior part areas	concentrates on exterior corner, edges	interior and exterior	exterior and interior similar	exterior-some interior	dependent on fixture orientation
Media/parts material handling	awkward with external separation	automated internal separation	manual or automatic	manual load, machine unload	manual or robotics
In-process inspection?	NO	YES	YES-usually	NO	NOT usually

Electropolishing

Electropolishing is a process by which metal is removed from a work piece by passage of electric current while the piece is submerged in an electrolyte. The process is essentially the reverse of electroplating. The work piece itself is dissolved, releasing metal ions into the solution. The work piece is made the anode and another terminal in the bath is the cathode. When a low voltage direct (DC) current is applied a polarized film forms over the entire surface of the work piece. This film is thickest over the microdepressions and thinnest over the microprojections on the surface. The current density is higher where the polarized film is thinner and therefore the rate of metallic dissolution is greater. Electropolishing literally dissects the metal crystal atom by atom, with rapid attack on the high current density areas and lesser attack on the low current density areas. The result is an overall reduction of the surface profile with a simultaneous smoothing and brightening of the metal surface. (see Figure 3.5) (Ward, 1984)

The quantity of metal removed from the work piece is proportional to the amount of current applied and the time. (Jumer, 1993) Other factors such as bath temperature, geometry of the work piece, bath chemistry, and incoming surface finish affect the distribution of current and, consequently, have an important bearing upon the resulting finish. Finishes from satin to mirror bright can be produced by controlling time, temperature, or both. Low temperature and short immersion time will produce satin finishes. Bright finishes are obtained by increasing time and temperature.

Electrodeburring is a special application of electropolishing. Burrs are removed from cut edges because electrolytic current flow is greater at edges and protrusions. Electrodeburring is essentially the same as electropolishing; however, the current densities are significantly higher to remove burrs preferentially.



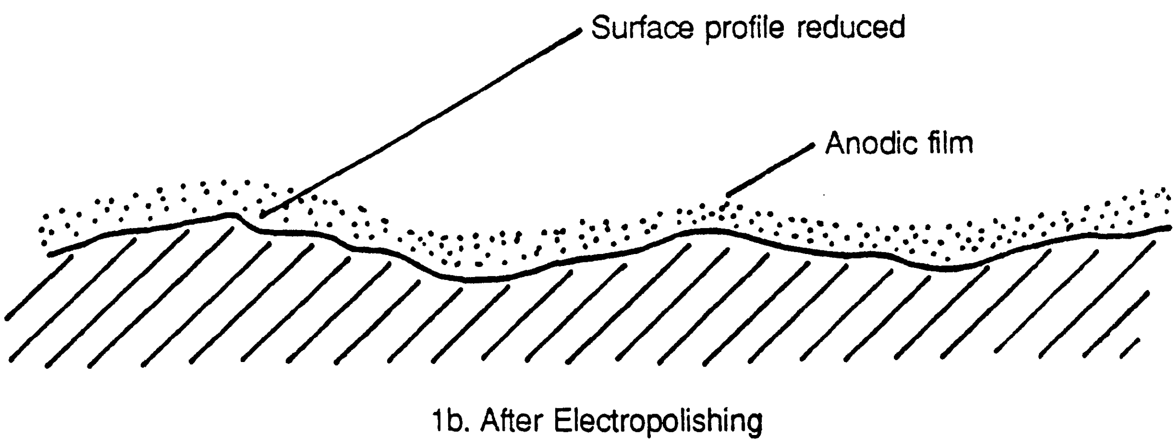


Figure 3.5 - Schematic illustration of low and high current density areas before and after electropolishing.

Passivation of Stainless Steel

In the case of stainless steel alloys, an important effect is caused by differences in the removal rates of the components in the alloy. Iron atoms are more easily extracted from the surface than are nickel and chromium atoms. For this reason, the electropolishing process removes the iron preferentially, leaving a surface rich in nickel and chromium oxides. Electropolishing passivates stainless steel to a greater extent than does any other passivation treatment. (Ward, 1984)

Some of the additional advantages and the disadvantages of electropolishing are listed below.

Advantages of Electropolishing

- handles all part sizes and shapes
- practical automated batch processing
- generally less expensive than mechanical finishing - low capital investment
- lower coefficient of friction than mechanically polished surfaces
- low labor cost
- suitable for fragile parts

Disadvantages of Electropolishing

- inability to achieve variable surface finish across the part
- waste disposal can be very expensive
- process variability may be difficult to control
- exposure risks to workers

- expensive exhaust and waste systems are required
- dedicated fixturing may be required for each product family

Environmental Concerns

One of the major disadvantages of electropolishing is that it generates several hazardous waste streams which can be very costly to dispose of. Rinse water is required to remove solution from the parts. These rinses usually go into drains and are subject to various regulations regarding discharge to public sewer treatment systems. Electropolishing baths generate both hydrogen and oxygen gases, producing an acid mist which must be ventilated to meet OSHA requirements. The metal ions that dissolve into the bath will eventually settle out as sludge containing chromium, iron, and nickel ions. This sludge must be disposed of as hazardous waste. The electropolishing baths themselves must periodically be replaced and the spent electrolyte must also be disposed of as hazardous waste. An electropolishing shop requires significant expense to handle the waste streams and considerable amounts of time to manage the regulatory paperwork.

Burlytic Processing

The Burlytic Process is a new method of electrolytic surface finishing that was invented in Sweden in 1980. The Debur Corporation was established in Massachusetts in 1987 to introduce this new form of finishing into the United States. Since then a number of systems have been delivered, and many more have been proposed. The method is applicable to a wide range of metals, including steels, stainless steels, aluminum alloys, copper alloys and magnesium.

The fundamental principle underlying the Burlytic Process is not new. It utilizes reverse electroplating in a manner similar to traditional electropolishing. There are, however, a few important distinctions. First, the voltage is not applied continuously, but rather in pulses. Second, the patented Burlyte electrolyte is non-aqueous; its base ingredient is ethylene glycol. Consequently, it has semi-conductive properties and higher electrical resistance than electrolytes used in traditional electropolishing. In combination these features produce a "peak effect", which causes selective dissolution of burrs and sharp edges. The degree of edge rounding and surface roughness reduction can be controlled by varying the cycle parameters. (Brenner, 1992)

The Burlytic Process is used primarily for deburring applications, but it has also been successfully employed to polish machined surfaces. Surface roughness in the range of 63-125 μin. R_a has been improved to 16-32 μin., and starting conditions of 16-32 have been polished to 4-8 μin. (Debur Tech. Paper, 1992) Most cycles take only a few minutes and some micro-deburring applications may take less than 30 seconds.

One advantage of the Burlytic Process is that tooling, if required, is generally simple and inexpensive. Many types of parts can be processed without tooling, on racks similar to those used in the plating industry. The process is computer controlled which allows any operator to achieve repeatable results lot after lot. The control computer can also store many different programs which may be required to process a variety of parts.

Another important advantage is that the Burlyte electrolytes are safe to handle. They are near-neutral, operate chilled (59°F), do not fume, and never require changing because they are not degraded in any way as a result of the finishing operations. Skin contact is not harmful and an exhaust hood is not required.

The Burlytic Process requires far less "tweaking" of process parameters than does traditional electropolishing. The only issue is that polishing does not occur on the surfaces of the part that are in contact with the fixture. Simple tooling racks can usually be designed to hold the parts at a location that does not need to be polished. The Burlytic Process passivates stainless steel to the same degree as traditional electropolishing. The following table (Brenner, 1992) presents a comparison of the Burlytic Process with traditional electropolishing.

Feature	**Electropolishing**	**Burlytic Processing**
Cathode spacing	large	large
Tooling cost	little or none	little or none
Electrolyte	hot acid (hazardous)	cool Burlyte (non-hazardous)
Electrolyte life	limited	unlimited
Electrolyte conductivity	high	semi-conductive
Bath maintenance	difficult	easy
Metals treated	most	most
Small/large burrs?	yes/no	yes/yes
Improves surface?	yes	yes
Process control	difficult	easy (computer controlled)
Exhaust provisions	essential	not required

Some limited tests have also revealed that brief treatment of cutting tool edges can extend operating life substantially. Milling cutters given Burlytic Process exposure for 15 seconds have shown up to 400% increase in useful life before resharpening. (Brenner, 1992) It is believed that the Burlytic Process micro-radiuses the cutting edges which reduces the stress concentration at the sharp corners. Lowering the stress concentration will reduce the likelihood of surface crack initiation.

Environmental Concerns

Like any electrochemical process, the Burlytic Process has two waste streams: hydroxide sludge and rinse water. During processing the metal ions dissolved off the parts will combine with hydroxyl ions from the electrolyte to form metal hydroxides. These hydroxides are filtered out of the electrolyte and the semi-solid sludge may require controlled disposal, particularly if stainless steel parts are processed. The Burlytic hydroxides will contain ethylene glycol, and a few other ingredients as opposed to sodium nitrate or sodium chloride found in traditional electropolishing wastes. Ethylene glycol is biodegradable, non-toxic, and considered harmless to the environment when disposed of properly.

The rinse water used to remove electrolyte and metal ions that cling to the part surface is the other waste stream. A low temperature distillation unit can be added to the system to achieve zero rinse water discharge, thereby eliminating the need for any discharge permits. The residue which remains after boiling off the electrolyte would be collected and disposed of with the sludge or returned to the finishing process tank for hydroxide conversion and filtration.

The electrolyte itself is primarily ethylene glycol, which carries the lowest industrial rating (1,1,1) in terms of its hazards. A 1,1,1 rating is the most desirable rating next to milk or potable water.

Chapter Four
Technical Cost Modeling

Codman, like many companies in the U.S., has increasing come under pressure to reduce production costs to be competitive with overseas manufacturers. Introduction of new process technologies is often performed to reduce production costs. While most companies have substantial engineering expertise available to sort through the myriad of processing technologies, few have developed a technique for detailed processing cost analysis. Technical cost modeling is a methodology which can be used to analyze the economic consequences of alternative manufacturing processes without the prohibitive economic burden of trial and error innovation and process optimization.

Technical cost modeling is an extension of engineering process modeling, with particular emphasis on capturing the cost implications of process variables and economic parameters. By grounding the cost estimates in engineering knowledge, critical assumptions, such as processing rates and energy and materials consumption, interact in a consistent manner to provide an accurate framework for economic analysis. These models are flexible, allowing users to tailor them to their own cost estimating environment. Once modified, these models can be used to explore in detail the costs of competing processes and materials for a particular application. Technical cost modeling has been successfully applied to a variety of different industries and process technologies. (Poggiali, 1985; Busch, 1987; Ng, 1990; Mangin, 1993)

A general description of the major components of technical cost models will be presented first, followed by a description of the specific finishing technology models developed for Codman. Finally, the results of the finishing models will be presented along with the sensitivity analyses.

Technical cost modeling approaches cost estimation by estimating the individual elements that contribute to total cost. These individual estimates are derived from basic engineering principles, from the physics of the manufacturing process, and from clearly defined and verifiable economic assumptions. Technical cost modeling essentially reduces the complex problem of cost analysis to a series of simpler estimating problems, and brings engineering expertise, rather than intuition, to bear on solving these problems.

In dividing cost into its contributing elements, a distinction is made between cost elements that depend upon the number of components produced annually, and those that do not. These two types of costs are called variable and fixed costs.

Variable Costs

Variable cost elements are those elements of piece cost whose values are independent of the number of pieces produced. The common variable cost elements are:

1. Material Cost
2. Direct Labor Cost
3. Energy Cost

Material cost refers to the actual cost of the raw material used to produce the part, including scrap costs. The cost of labor is a function of the wages paid, the time required to produce a part, the number of laborers associated with the process, and the productivity of this labor. Labor wages should include the cost of benefits to the laborer, such as health insurance and retirement benefits. The cost of supervisory or other overhead labor are accounted separately as overhead labor costs. The cost of energy refers to the cost of electricity, steam, or other forms of energy used to produce each part.

Fixed Costs

In contrast with the variable costs, the fixed costs are those elements of piece cost which are a function of the annual production volume. The common elements of fixed costs are:

1. Main Machine Cost
2. Auxiliary Machine Cost
3. Building Cost
4. Overhead Labor Cost
5. Maintenance Cost
6. Cost of Capital

There are two basic problems to be resolved in all fixed cost estimates: first, establishing the size of the capital investment or annual expense, and second, determining the most reasonable basis for distributing this investment or expense over the products manufactured.

Main Machine Cost

The cost of the main machine is usually a direct function of its capacity. How to determine the appropriate size machine depends on the specific process technology, the product demand, and many other parameters related to a particular company and industry.

A consistent procedure must be established for distributing the investment over the production volume. The simplest method to distribute cost is as follows:

$$\text{Cost per part} = \frac{\text{annualized investment}}{\text{annual production volume}}$$

In this equation, the annual investment cost is evenly divided onto the parts produced in a year. Annual investment is equal to the total investment cost divided by the number of years the machine will be in service.

The equation above assumes that the machine is dedicated to the production of one particular part and that the annual production volume will fully utilize the machine. In most cases, one or both of these assumptions is not valid. For situations involving partial machine utilization, or when many different parts are produced on the same machine, the following equation may be more appropriate:

$$\text{Cost per part A} = \frac{\text{annualized investment}}{\text{annual production volume of part A}} \times \frac{\text{production hours for part A}}{\text{total production hours}}$$

The total annualized investment is again divided by the annual production volume of a particular part, but in this case, it is also multiplied by a fraction, the ratio of the time required to complete the production run to the total available time. If only half a year is required for a production run, only half of the annual investment cost will be distributed onto those parts. This method is equivalent to charging rent for the use of the machine.

Either one of these two capital distribution formulae may be valid in different cases; neither one is universally applicable. In practice, many companies operate somewhere between the two extremes represented by these equations. Such companies cannot dedicate a machine to the production of one part, but neither can they keep their machinery fully utilized. For these situations, the two equations provide a means of bracketing the machine cost on a per part basis.

Auxiliary Equipment Cost

For surface finishing technologies, typical auxiliary equipment could include water treatment systems, air filtering systems, and particulate collection systems. The contribution of auxiliary equipment to the cost of the part can be estimated using one of the two capital distribution equations mentioned above.

Building Cost

The investment cost of the required building space is relatively straightforward to estimate given the amount of space required and the price per square foot of factory floor space. Distributing the building investment onto the parts can be done using whichever of the capital distribution equations described earlier is more appropriate.

Overhead Labor Cost

Overhead labor costs are the salaries of supervisors, managers, janitors, etc., not directly associated with the production process. The contribution of overhead labor cost to part cost is virtually impossible to estimate explicitly, unless the operation in question involves the production of only one component. The most common way of accounting overhead labor is through the use of a variable burden rate, wherein the ratio of overhead labor to direct labor cost is set at a constant value.

Maintenance Cost

The cost of maintaining capital investments is also difficult to quantify precisely. Maintenance is often unscheduled, done in response to problems as they develop. To accurately estimate the cost of maintenance requires accurately predicting probabilistic events. One common approach to estimating maintenance costs assumes that they are equal to a fraction of another cost element, usually the cost of the investment that is being maintained.

Cost of Capital

The cost of capital is a fixed cost element that accounts for the time value of money. Deciding whether or not to include the cost of capital in a technical cost model depends on what decisions are going to be made based on the results of the model. If the model's results are going to be used as inputs to a net present value (NPV) calculation for the capital investment decision, than the cost of capital should not be included in the cost model. The NPV calculations will account for the cost of capital and including it in the cost model will result in double-counting.

If, however, the cost model is only being developed to estimate the initial production costs for a new technology, than the cost of capital can be included in the model to reflect the cost of borrowing the money to invest in the new technology. When comparing different technologies, inclusion of the cost of capital will capture the difference in costs of new technologies which require significantly different capital investments. The remainder of this section describes one method for computing the cost of capital for technical cost models.

The cost of capital is equivalent to the interest portion of a loan payment, and is considered to be a fixed cost because, over the course of an accounting period, its total value is independent of the production volume. On a piece cost basis, the cost of capital varies inversely with production volume.

Equations for estimating loan payments can be found in most textbooks on engineering economics. While there are a number of variations to these equations, the simplest and most widely used is the simple-interest capital recovery equation, presented below.

$$\text{Payment} = \text{Investment} \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right)$$

In this equation, "i" is the interest rate and "n" is the number of periods over which the investment is recovered. The term within the parenthesis is called the capital recovery factor.

The above equation calculates total payments, including both the interest and principal portions of capital recovery. However, the "cost of capital" element is just the interest portion of this total. To isolate the interest portion, the principal is subtracted from the total. In the models presented in the following section, it is assumed that the principal portion is constant in all payment periods. The quotient of the investment divided by the number of payment periods is subtracted from the payment value calculated above. The equation for computing the cost of capital becomes:

$$\text{Cost of Capital} = \text{Investment} \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} - \frac{1}{n} \right)$$

This equation computes the average "cost of capital" over all capital recovery periods. Computing the cost of capital in this manner eliminates the need for knowing the age of an investment by treating the interest portion as if it is constant throughout all recovery periods. For most loans, this is not true. Rather, the initial payments consist of mostly interest, while the final payments are mostly principal.

The alternative to this approach is to establish the age of each capital investment, and use this information to accurately compute the interest and principal fractions of capital recovery. For the purposes of general cost estimation, this is rarely worthwhile. Only when tax considerations are important is it worth the added effort, since taxes are affected by the interest and principal portions of capital recovery in different ways.

Summary of Technical Cost Analysis

The preceding sections introduced the concepts of variable and fixed cost elements, and provided examples of each. The key principles of technical cost analysis are:

1. Primary and secondary processes contribute to the cost of a finished part.
2. The total cost of a process is made up of many contributing elements that can be classified as either fixed or variable, depending upon whether or not they are effected by changes in the production volume.
3. Each element can be analyzed to establish the factors and the nature of the relationships that effect its value.
4. Total cost can be estimated from the sum of the elements of cost for each contributing process.

With this general description of technical cost modeling explained, the remainder of this chapter is devoted to a detailed explanation of the cost models developed for surface finishing technologies.

Technical Cost Models for Surface Finishing Technologies

Technical cost models have been developed for the following surface finishing technologies:

- manual finishing
- centrifugal disc finishing
- centrifugal barrel finishing
- vibratory finishing
- Burlytic processing

The models have all been written as spreadsheets in Microsoft Excel, version 4.0 for PC compatible computers. Each model consists of five "pages" or sections: factor prices, input factors, production calculations, cost calculations, and cost summary. The first two sections, factor prices and input factors, are where all of the process data are entered by the user. The production and cost calculations sections are where the computer performs all of the calculations. The user may not change any of the cells in these sections since they contain the formulas that model the processes being analyzed. The cost summary section provides a detailed breakdown of all of the fixed and variable costs associated with production of each part. Please note that the term 'part' is used throughout the models to denote the component (assembled instrument or piece-part) that is being processed. Each of the five sections will be explained separately.

Warning!!

The technical cost models presented in this thesis are just models, meaning they do not describe reality with 100% accuracy. The user should not blindly rely on the numbers generated by the models. Many of the formulas used in these models are estimations based more on qualitative experience than rigorous, scientific experimentation. In particular, the production calculations should only be used as good "starting points" for a process and should subsequently be validated by actual production testing. The cost data generated by these models are based on technical cost modeling techniques and should not be used in comparison with traditional cost accounting data. The cost data should only be used to compare costs of processes that have been estimated using technical cost modeling.

Factor Prices

The factor prices refer to the actual price or value of the inputs to the model. The major categories are: energy, process materials, equipment, labor, and capital-related charges, as shown in Figure 4.1. Factor prices are entered by the user and can be varied causing the model to automatically update the production and cost calculations. The inputs for energy and process materials are clearly noted on every model. Equipment includes the price of the main machine, any auxiliary equipment (i.e. J Press for centrifugal disc machine), and installation. For cases in which the company already owns the equipment, the salvage value of the equipment should be used since this is the "opportunity cost" of the equipment. Labor inputs include the wage rate and the overhead burden rate. The total wage is calculated automatically by the model.

The capital-related charges include values related to capital investment. The cost of capital, or hurdle rate, is required to estimate the time value of money. Insurance costs are typically estimated a percentage of the physical equipment. Maintenance costs are inputted as either a percentage of the physical equipment or as a yearly cost, depending on the specific model. Please note that the useful life of the equipment and the years to recover the investment may be significantly different and thus are inputted separately.

FACTOR PRICES

Energy			
	Electricity	$0.0834	$/Kwh
Process Materials			
	WK,ACT,3/8"x1/4"	$0.81	$/lb.
	Compound	$20.00	$/gal.
Equipment			
	Rotomax RM-6A	$94,150	
	Auxiliary equipment (J Press)	$5,000	
	Installation cost	$1,000	
Labor			
	Wage rate	$12.00	$/hour
	Overhead burden rate	400%	
	Total wage	$60.00	$/man-hr
	Working days per year	240	
	Number of shifts per day	1	
	hours per shift	8	

Capital-Related Charges			
	Cost of Capital (% of initial investment)	18.0%	
	Insurance (% of physical equipment)	1.0%	
	Maintenance (% of physical equipment)	2.0%	
	Useful life of equipment	10	years
	Years to Recover Investment	3	years

Figure 4.1 - "Factor Prices" page from a centrifugal disc finishing cost model.

Input Factors

The cost of producing a product is affected by a number of external parameters referred to as input factors. The specific inputs vary depending on which process is being modeled. Figure 4.2 shows the input factors for a centrifugal disc finishing model. Typically there are inputs for process material usage rates. For mass finishing processes, these would be media wear rate and compound concentration and flow rate. For the Burlytic process these would be electrolyte usage and power consumption. The mass finishing models also include inputs for equipment dimensions and motor size. These data are used to calculate the working capacity and energy usage of the equipment.

The other major input factors are production volume, cycle time, labor content, and parts processed per cycle or part dimensions. For all of the models except the manual finishing model, there are inputs for production data for up to three different parts. This allows the model to make calculations for a machine that is not dedicated to the processing of one part. The primary part is the part for which the cost calculations will be performed. The data for the 2nd and 3rd part are used to perform the production capacity calculations and to allocate the equipment costs for a non-dedicated machine. If the model is being used for a dedicated machine, zeros should be entered for the production volumes for the 2nd and 3rd parts.

For mass finishing models, the processing calculations are based on a series of relationships developed by John Kittredge (1981). The user must input three part dimensions: A, B, and C. Dimension A represents the largest part dimension, usually the overall length of the instrument. Dimension B is the largest dimension perpendicular to dimension A. Dimension C is the largest dimension perpendicular to dimension B. These dimensions should be entered such that $A \geq B \geq C$. These dimensions are used to calculate the average rotational volume of each part, which is then used to determine the number of parts that can be processed per cycle.

INPUT FACTORS

Primary Finishing Process:	Wet Cut Down of Scissors
Labor productivity	85%
Equipment working capacity	6.00 cu. ft.
Motor horsepower	10.0 hp
Motor efficiency	75%
Media wear rate	0.700 %/hour
Media density	100 lbs/cu. ft.
Compound concentration	2.0 oz/gal
Compound flow rate	10 gal/hour
Prod. volume for primary part	36,000 parts
Process time for primary part	1.00 hours/cycle
Labor content for primary part	0.300 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.50 inches
Smallest, C	0.25 inches
RV factor for primary part	0.63
Prod. volume for 2nd part	6,500 parts
Process time for 2nd part	1.00 hours/cycle
Labor content for 2nd part	0.167 hours/cycle
Dimensions - Largest, A	9.25 inches
Middle, B	3.50 inches
Smallest, C	0.25 inches
RV factor for 2nd part	0.63
Prod. volume for 3rd part	150,000 parts
Process time for 3rd part	1.00 hours/cycle
Labor content for 3rd part	0.300 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.75 inches
Smallest, C	0.20 inches
RV factor for 3rd part	0.63

Figure 4.2 - "Input Factors" page from a centrifugal disc finishing cost model.

An RV factor for each part must also be entered in the mass finishing models. The RV factor is a multiplier which will modify the media-to-parts ratio for the many types of parts and conditions involved in the mass finishing process. Essentially the RV factor is used to determine how much part-on-part contact will be allowed during the process. The following chart details the range of practical RV factors and gives qualitative descriptions for when to use each factor. A higher RV factor will increase the number of parts processed per cycle and thus increase the amount of part-on-part contact.

Rotational Volume Factors

RV Factor	Description of Rotational Volume Factor
2.5	Very heavy part loading. Constant contact between parts. For crude, very rough work, like forgings.
2.0	Somewhat better. Still very rough work.
1.6	More part separation. Severe part-to-part contact.
1.26	Fair-to-good for ferrous metals. About minimum for non-ferrous parts. Considerable contact.
1.00	Good for ferrous metals. Fair-to-good for non-ferrous work. Some contact depending on media size.
.8	Very good for ferrous metals. Good for non-ferrous parts. Modest contact between parts.
.63	Excellent for ferrous, very good for non-ferrous, even pre-plate quality.
.5	Very high quality finishes. Good for fragile parts
.4	Less contact. Exceptional quality.
0	When no two parts can be permitted to contact one another. Fixture one part per compartment or machine.

When the media size is large, use the next lower factor. For wet cut down of parts, an RV factor of .63-.8 should be acceptable. For final finishing, a RV factor of .63 or less should be acceptable. Experience with specific media and parts will determine the most appropriate RV factors for future calculations.

Production Calculations

There are no user inputs in this section; the data are generated by the model. For mass finishing processes, the model calculates the average rotational volume of each part and uses this number and the RV factor to calculate the maximum number of parts that can be processed per cycle. A detailed description of the equations used in this section can be found in "The Mathematics of Mass Finishing" by John Kittredge (1981). All of the models estimate the required production hours while adjusting for the labor productivity rate determined by the user. The last part of this section shows the total production hours required to process all of the different parts. A message will be printed to show whether the estimated production hours are within the current capacity of the machine. An example of the "Production Calculations" layout is shown in Figure 4.3. This section is included in the models for use in capacity planning.

Cost Calculations

All of the cost calculations are performed by the model in this section; there are no user inputs. All of the fixed and variable costs are calculated and tabulated separately, as shown in Figure 4.4. The calculations for each variable cost are typically broken down as units per cycle, then cost per cycle, and finally cost per part. This is done so the user can view the simplified formulas in each cell instead of one large formula which would be difficult to understand.

The cost of equipment is broken down into annual payments spread evenly over the useful life of the equipment. The equipment cost per part is determined by distributing

PRODUCTION CALCULATIONS

Primary part		
Average rotational volume	36.53	RV/cu. ft.
Parts processed per cu. ft.	23.02	parts/cu. ft.
Parts processed per cycle	138	parts/cycle
Total cycle time	1.353	hours/cycle
Projected production hours	353	hours
2nd part		
Average rotational volume	15.07	RV/cu. ft.
Parts processed per cu. ft.	9.49	parts/cu. ft.
Parts processed per cycle	56	parts/cycle
Total cycle time	1.196	hours/cycle
Projected production hours	139	hours
3rd part		
Average rotational volume	33.10	RV/cu. ft.
Parts processed per cu. ft.	20.85	parts/cu. ft.
Parts processed per cycle	125	parts/cycle
Total cycle time	1.353	hours/cycle
Projected production hours	1,624	hours
Total production volume	192,500	parts
Total projected production hours	2,115	hours
Total available production hours	1,920	hours

The projected production hours EXCEED current capacity.

Figure 4.3 - "Production Calculations" page from a centrifugal disc finishing cost model.

COST CALCULATIONS

Process Material Cost		
Compound usage per cycle	20.0	oz/cycle
Compound cost per cycle	$3.13	$/cycle
Compound cost per part	$0.02	$/part
Media usage per cycle	4.20	lbs/cycle
Media cost per cycle	$3.40	$/cycle
Media cost per part	$0.02	$/part
Energy Cost		
Energy usage per cycle	10.00	kwh/cycle
Energy cost per cycle	$0.83	$/cycle
Energy cost per part	$0.01	$/part
Labor Cost		
Labor content per cycle	0.353	hours/cycle
Labor cost per cycle	$21.18	$/cycle
Labor cost per part	$0.15	$/part
Equipment Cost		
Total equipment cost	$100,150	
Annual equipment cost	$10,015	$/year
Equipment cost per part	$0.05	$/part
Capital Costs		
Annual cost of capital	$12,678	$/year
Cost of capital per part	$0.06	$/part
Insurance per part	$0.00	$/part
Maintenance per part	$0.01	$/part

Figure 4.4 - "Cost Calculations" page from a centrifugal disc finishing cost model.

a portion of the annual equipment cost evenly over the production volume of a particular part. The portion of the equipment cost allocated is simply the percentage of production hours that the equipment is dedicated to processing a particular part, following the capital distribution equation for non-dedicated equipment explicated earlier in this chapter.

The capital costs are allocated in the same manner as equipment costs, as a percentage of equipment time dedicated to a particular part. The cost of capital is a fixed cost element that accounts for the time value of money. The cost of capital is calculated using the equation developed earlier in this chapter. It should be noted that in periods after the investment has been recovered, the cost of capital element would become zero.

Cost Summary

This section is simply a summary of all of the variable and fixed costs associated within processing a particular part. The percentage of the overall production cost is given for each individual cost element, as shown in Figure 4.5.

Cost Summary for Wet Cut Down of Scissors

Variable Cost Elements

	$/part	percent
Process material cost	$0.05	14.5%
Energy cost	$0.01	1.9%
Direct labor cost	$0.15	47.1%
TOTAL VARIABLE COST	$0.21	63.5%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.05	14.2%
Maintenance cost	$0.01	2.8%
Cost of capital	$0.06	18.0%
Insurance	$0.00	1.4%
TOTAL FIXED COST	$0.12	36.5%

	$/part	percent
TOTAL FINISHING COST	**$0.33**	**100%**

Figure 4.5 - "Cost Summary" page from a centrifugal disc finishing cost model.

Model Results

The complete printouts of a cost model for each technology are provided in Appendix A. However, a summary of the fixed and variable costs associated with each process technology and application is presented in the following table.

Application	Process	Fixed Cost Per Part	Variable Cost Per Part	Total Cost Per Part
Cut down and polish of rongeurs	manual finishing	$0.03	$8.86	$8.89
Cut down of rongeurs	cf. disc (3 cu. ft.)	$0.12	$0.61	$0.73
	cf. disc (6 cu. ft.)	$0.26	$0.34	$0.60
Dry polishing of rongeurs	cf. barrel (3.8 cu.ft.)	$1.21	$1.14	$2.35
	cf. barrel (4.8 cu.ft.)	$1.43	$0.95	$2.38
	cf. barrel (6.0 cu.ft.)	$1.87	$0.79	$2.66
Cut down of scissors	cf. disc (3 cu. ft.)	$0.05	$0.28	$0.34
	cf. disc (6 cu. ft.)	$0.12	$0.21	$0.33
Cut down of scissors	vibratory tumble	$0.03	$0.34	$0.37
Bright finishing of scissors rings	Burlytic process	$0.22	$0.34	$0.56
Cut down of Boxlock	cf. disc (3 cu. ft.)	$0.06	$0.32	$0.38
	cf. disc (6 cu. ft.)	$0.13	$0.23	$0.36
Bright finishing of Boxlock	Burlytic process	$0.26	$0.40	$0.66

While the processing costs vary from technology to technology, all of the automated process technologies offer substantial cost savings when compared to the current manual finishing process.

Sensitivity Analysis

The real power of technical cost models developed on computer spreadsheets is the ability to perform sensitivity analyses quickly. Using the "Scenario Manager" in Excel, it is easy to view the effects of one or more input variables on the fixed and variable costs of a process. All of the input variables in each cost model were varied within reasonable upper and lower limits to identify the major cost drivers in the process. The following paragraphs summarize the results of the sensitivity analyses performed for each process.

The major cost drivers for the centrifugal disc process are the RV factor and the labor content per process cycle. This is true for both the three cubic foot and the six cubic foot machine. All other inputs have little or no effect on the cost per part. The fixed costs for this process are relatively low. The RV factor directly affects the number of parts processed per cycle, which subsequently affects the cost per part. Lowering the RV factor from 0.63 to 0.5 causes roughly a 20% increase in the total processing cost per part for either size machine. Increasing the labor content per cycle by five minutes also raises the total cost by about 20%. Therefore, lower centrifugal disc finishing costs can best be achieved by reducing the time required for loading and unloading the machine and increasing the number of parts processed per cycle. Labor content is not as significant for the six cubic foot machine as it is for the three cubic foot machine because the number of parts per cycle is greater.

The major cost drivers for centrifugal barrel finishing are the same as for centrifugal disc finishing. In addition to labor content and RV factor, the cost is also greatly affected by the size of the machine. As the capacity of the machine increases, the variable cost decreases because more parts can be processed per cycle. However, the fixed cost increases as the machine capacity increases because the higher equipment costs are allocated over the same number of production volumes. This process is relatively expensive compared with the other processes because it is labor intensive and fewer parts can be processed per cycle due to the high quality finishes required.

The major cost drivers for vibratory finishing are RV factor, process time, media wear rate, and labor content. This process uses a relatively large amount of media so the process time and wear rate are significant. The major costs are media and labor so reducing the amount of media used per cycle and the time to load and unload the machine are the best ways to lower finishing costs. The fixed costs are almost zero for this process since Codman already owns the machine.

The cost for Burlytic Processing is not sensitive to electricity cost, electrolyte cost or usage, sludge disposal cost or process time. The only significant cost drivers are labor content per cycle and the cost of capital. The cost of capital is important because of the relatively high cost of the equipment (over $175,000). Changes in the cost of capital affect the fixed cost per part. Because of the relatively small process lot size (10-12 parts per cycle), increases in the labor content per cycle greatly affect the cost per part. The lowest process cost can be achieved by keeping the load and unload time within the process cycle of three minutes.

Summary

In general, the total cost per part for all of these automated finishing processes is primarily driven by labor content. The process material, energy, and equipment costs are relatively small on a per part basis. All of these processes are significantly lower in cost than manual finishing. The cost for each process, except centrifugal barrel finishing, is under $1.00 per part while most equivalent manual operations are at least $5.00 per part. On a purely cost basis, the processes can be optimized by automating part loading/unloading and increasing the process lot size.

Chapter Five
Conclusions & Recommendations

All of the technologies investigated showed some potential. However several technologies do not measure up against the other technologies based on Codman's key criteria. Codman's key criteria are the processing cost per part, flexibility to process different instruments, and the development time required to implement the new technology. Robotic finishing and electropolishing do not satisfy Codman's needs as summarized below. Several mass finishing processes and the Burlytic process are very promising. They yielded acceptable results and all of them would significantly reduce production costs. The conclusions for robotic finishing and electropolishing are presented first, followed by a set of recommendations for investment and the reasons supporting those recommendations. The last section of this chapter presents some recommendations for future research.

Conclusions for Robotic Finishing

Due to the wide variety of products and the low production volumes, a robotic finishing system can not be justified economically. The state-of-the-art in robotic finishing is suitable for high volume, low variety applications. The fixturing required to grip the many different sizes and shapes of Codman products would be extremely expensive. Lengthy programming time would be required to set up the robot to polish the variety of instruments.

High volume shaping operations, such as the outside rings and shanks, would be the best applications for robotic finishing. However, there are other automated finishing systems that can perform these operations with a significantly lower capital investment.

Codman should pursue simpler robotic applications such as pick-and-place robots to obtain some experience with robotic systems. This would reduce the development time required for implementing the more sophisticated systems used for robotic finishing.

Conclusions for Electropolishing

Electropolishing can be a very difficult process to control and thus a joint development effort with a vendor would be required for Codman to achieve process control for the wide variety of instruments it produces. This development effort would probably take a considerable amount of time. Initial test samples processed by several vendors revealed that uniform, consistent finishes would be difficult to attain considering the complex geometry of Codman's instruments.

Although the process equipment is relatively inexpensive, the exhaust and waste disposal systems necessary to support production make implementation of this technology rather expensive. Furthermore, as the environmental regulations become more restrictive and liability becomes wider reaching, it would not be a good strategic move to invest in such an environmentally-unfriendly technology.

Recommendations for Investment

1. Purchase a fully automated six cubic foot working capacity centrifugal disc machine and sell the existing three cubic foot machine. (Net cost would be $50,000-$60,000)

2. Purchase the 500 amp Burlytic Processing system, including a low temperature distillation unit for rinse water processing. (Total cost would be about $185,000)

3. Purchase a centrifugal barrel machine for dry finishing; machine size would depend on the acceptable applications. (Total cost would be between $5,000 and $50,000)

Conclusions for Centrifugal Disc Finishing

Although Codman's three cubic foot centrifugal disc has the capacity to process the required volumes, it cannot process instruments longer than seven inches. A six cubic foot machine should be able to process instruments up to ten inches long. A larger machine would also be able to process larger lots which would reduce the cost per part. A larger machine would be able to perform cut down for scissors, rongeurs, and all Boxlock instruments. I recommend purchasing a fully automatic machine in order to reduce the labor time required to load and unload parts and media. An overhead crane system for a six cubic foot machine could be very cumbersome and potentially dangerous. The automatic machines quickly and safely load the parts and media into the disc. Additional research should be performed to identify the best machine design and price.

Conclusions for Burlytic Processing

The Burlytic Process is an environmentally-friendly alternative to electropolishing and is the best technology for bright finishing. This system could easily handle all bright finished Boxlock instruments and all scissors rings and would eliminate the need for a separate passivation operation. The cycle times of three minutes or less would provide Codman with increased manufacturing flexibility and a significant decrease in lead times as well as processing cost. Once in-house, this process could also be applied to a variety of other applications, such as part deburring and micro-radiusing of milling cutters. Although the price tag for this equipment is relatively high, I think it would be a good strategic move for Codman to make the investment. Debur Corporation would provide Codman with a turn-key system for bright finishing, and once Codman gained some experience with the process additional applications could be explored.

Conclusions for Centrifugal Barrel Finishing

Dry finishing in the centrifugal barrel machine can produce some attractive surface finishes. Bright finishes can be achieved but several medias are required and the cycle times are relatively long. The Burlytic Process is a more cost efficient method for achieving bright finishes. Attractive satin finishes on rongeurs can be attained in the centrifugal barrel in a reasonable cycle time. These finishes are different in appearance than the traditional "brushed" satin finish using soft wheels and compound. If the market will accept the new satin look then this process is suitable and I would recommend purchasing a 4.8 or 6.0 cubic foot machine.

Centrifugal barrel finishing has also worked well for light deburring and brightening of titanium bone screws. If this process is found to be unsuitable for finishing rongeurs, then I would recommend a small, table-top, machine with a capacity of 0.35 cubic foot. This small machine could be dedicated to processing bone screws. A more detailed financial analysis should be performed to determine if the production volumes of bone screws alone would justify purchasing a machine.

Future Research

This study, while broad and relatively detailed, is not the last word on automated finishing technologies. Furthermore, there are areas other than the technologies themselves that could be studied in the future. I recommend the following areas for future research and investigation:

1. Automated abrasive and nonabrasive blasting systems
2. Design for automated finishing
3. Competitive benchmarking
4. Market acceptance of mass finishes

Abrasive and nonabrasive blasting technologies is the one major finishing topic that was not investigated. Significant advances in automated blasting have been made in recent years and thus automated blasting systems could potentially replace Codman's manually operated blasting cabinets.

Once a substantial commitment has been made to invest in automated finishing technologies, it is important to take full advantage of these processes. New products as well as existing products should be designed to be easily processed by the automated systems. Different design parameters should be tested and optimized for the new technologies. Subsequently, new design guidelines should be adopted so that products are designed to be automatically finished.

Competitive benchmarking is another area in which Codman could devote more resources. Understanding how the competitors finish their instruments could significantly reduce the research time needed before deciding to invest in new technologies. Reverse engineering of a competitor's processing technology is difficult, however a wealth of information can be obtained on which areas of the instruments are finished and to what degree. Companies competing in different industries can often be the best source of process information because they are usually willing to open their doors to a non-competitor.

An extension of benchmarking is the area of market research of surface finishes. As the health care industry changes, the customers' concerns about cosmetic surface finish and product cost are likely to change as well. Understanding what value the customers place on the surface finish and what they are willing to pay for it is crucial to successful marketing of surgical instruments. For example, customers may be willing to accept a "slightly less attractive" finish on an instrument if the cost can be reduced significantly. Market research is needed in order to quantify these relationships between quality of surface finish and product cost.

If the investments are made in the technologies investigated in this study and the areas recommended for future research are pursued, Codman will be able to maintain its successful position as a world-class manufacturer of surgical instrumentation.

Chapter Six
The Evolution of Work Design

Since the beginning of the 20th century there have been numerous studies and many different approaches taken towards the designing of work. The modern work designer has a wide variety of criteria available to determine what is a "good" job design. This chapter contains a brief overview of the evolution of work design models starting with the work of Frederick Taylor and concluding with a job design model based on sociotechnical systems theory. Some of the major contributions towards the advancement of job design models are presented to provide the reader with an understanding of how theorists and practitioners have approached work design during the past century.

Taylorism

Many believe that the origins of modern work design can be traced to the work of Frederick W. Taylor, the father of scientific management. Taylor published his "Principles of Scientific Management" in 1911 and they were widely used and misused throughout the first half of the 20th century. Taylor believed that substantial gains in efficiency and productivity could be achieved by breaking down each operation into a set of discrete tasks which would require minimal training time. Industrial engineers performed time studies for each task and standards were set. Compensation was often linked to performance against the standard.

Taylor, like pioneers in other fields, is often misunderstood. Taylor's overriding objective was productive labor-management cooperation. (Weisbord, 1987) In fact, Taylor viewed the industrial engineer as the third party facilitator between labor and management. He believed that systematic analysis of operations and standardization of tasks would help alleviate labor-management conflicts.

Taylor, however, did not understand the power of shared influence and joint decision making. He opposed group tasks and group incentives, arguing that they reduced accountability and could not be studied systematically. Taylorism facilitated the rise of mass production, but it created boring monotonous jobs and resulted in a splintering of knowledge. (Klein, 1993) The narrow skills required for each task created an inflexible work force. Weisbord (1987) states, "In time Taylorism became synonymous with speedups, employer insensitivity, people turned into robots, doing more work for the same pay instead of working smarter, producing more, and taking home fatter paychecks." (p. 61) Taylorism subdivided the system to such an extent that nobody had a whole view of what was being done.

Sociotechnical Systems

It wasn't until the early 1960's that Fred Emery and Eric Trist achieved the conceptual breakthroughs needed to bring systems thinking to the workplace and undo Taylorism. They realized that there is always an interaction of people (a social system) with tools and techniques (the technical system). They proposed an open systems approach to work design which requires social systems to be designed integratively with technical systems. Their approach has become known as sociotechnical systems (STS) design. STS design optimizes the whole system not each task, which is a major break from Taylorism. STS designers attempt to jointly optimize the requirements of the social system as well as the technical system. The goal for STS designers is to reduce the need for management and supervision by increasing skills and responsibility lower down in the organization.

In the 1970's, sociotechnical systems design became a popular analytical technique for work design and redesign. Emery and Trist (1978) published a step-by-step model for performing an STS analysis. The major steps in the process are summarized below:

1. **Scanning** - identify the production system and environment and initially (but not irrevocably) define the design system boundaries.
2. **Identification of Unit Operations** - identify the main segments in the production process - each unit operation effects an identifiable transformation in the incoming material.
3. **Identification of Key Variances** - identify the key variances, the most critical breakdowns in the technical process, and the interrelationships between them.
4. **Social System Analysis** - identify the main characteristics of the *existing* social system, including issues such as coordination, control and decision making.
5. **Sociotechnical System Design** - recombine the results of the technical and social system analyses such that control of the key variances is possible within the boundaries of the work system.

James Taylor (1975) sums up the STS design process well by stating, "The major sociotechnical design criterion...is that control of key variances, and the coordinating for that control (where such coordination is necessary) be placed at the lowest level at which there is both a technical subsystem (a meaningful transformation), and a social subsystem (two or more people relating to one another)." (p. 22) STS designers attempt to give the employees the proper authority, the proper information, and the appropriate skills to respond to variances in the manufacturing system at the point where they occur, when they occur. This is usually accomplished through the formation of semi-autonomous work groups, which is one of the major contributions of the sociotechnical approach to the theory and practice of work design.

Internal Motivation and Job Satisfaction

The evolution of work design took another step forward with the research efforts of J. Richard Hackman and Greg R. Oldham in the late 1970's and early 1980's. They focused squarely on the actual work performed by people and how the work design affected each individual's motivation. They proposed that high internal motivation leads to improved work effectiveness and increased job satisfaction. (Hackman & Oldham, 1980) Therefore it is important to understand what motivates people so that the work can be designed to create high motivation levels. Their theory suggests that there are three critical psychological states that must be present for a person's internal motivation to be high. These states are shown in Figure 6.1 below.

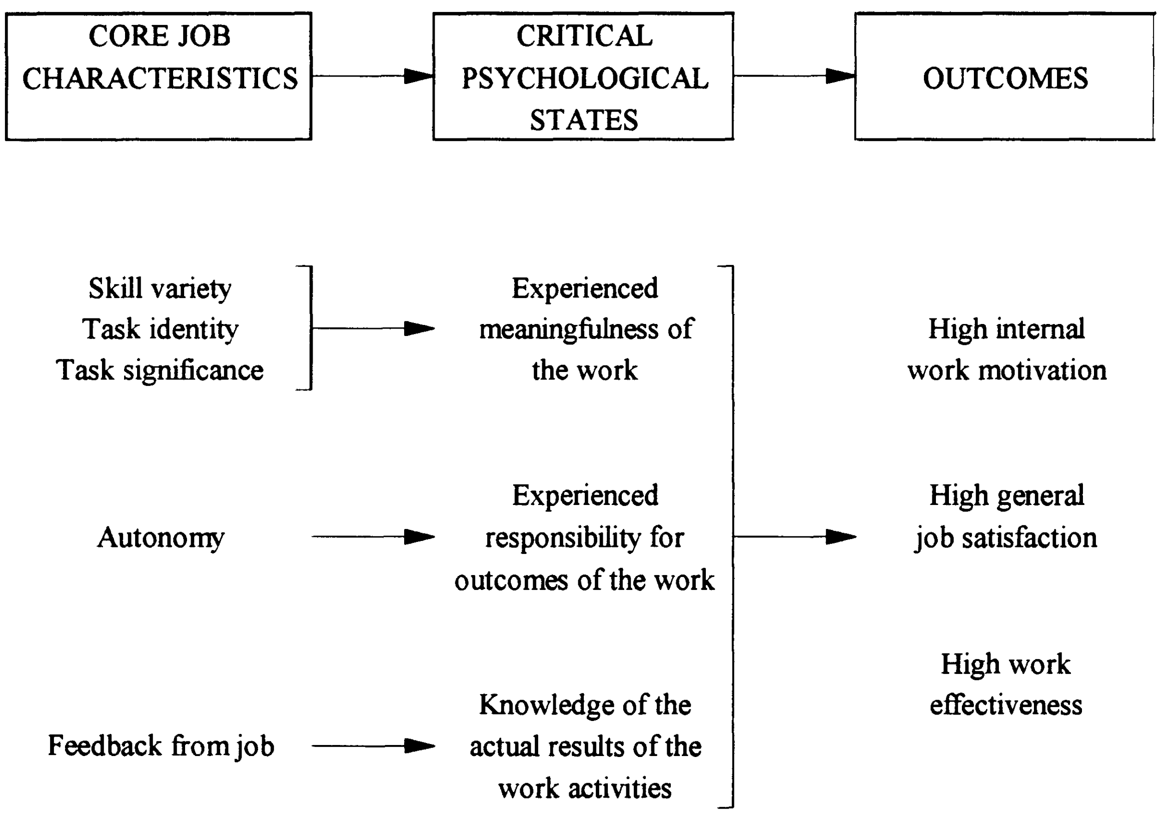


Figure 6.1 - Job Characteristics Model (Hackman & Oldham, 1980, p. 90)

Most people will be unmotivated at work when their tasks are designed so that they have little meaning, when they experience little or no responsibility for the outcome of the work, or when they are not informed of the results of their work activities. Hackman and Oldham (1980) suggest that "...motivation at work may actually have more to do with how tasks are designed and managed than with the personal dispositions of the people who do them." (p. 76)

The five core job characteristics shown in Figure 6.1 are the measurable, changeable properties of the work itself that foster the psychological states. For example, knowledge of the results of one's work is directly affected by the amount of feedback one receives from doing the work. Task identity, the degree to which a job requires completion of a "whole" piece of work, can influence the experienced meaningfulness of work. While it may be impractical to design jobs such that all five job characteristics are maximized, this model does give the work designer a framework for analyzing the motivating potential for each job design.

It should also be noted that creating the critical psychological states will also result in high general job satisfaction and high work effectiveness. Job enrichment may lead to improved general satisfaction, but there is no reason to expect that it should also lead to specific improvements in satisfaction with job security, supervision, pay, or co-worker relationships. Improvements in work effectiveness are manifested by higher levels of quality and quantity of the goods or services produced.

Toyota Production System

The Toyota Production System, as devised by Taiichi Ohno, is an example of STS design for autonomous work groups. Ohno designed the work groups to satisfy the need for greater work force flexibility. He was able to achieve this flexibility by creating a work structure where team members were trained to perform all the tasks within the team. Each worker in a team of eight to ten people would learn how to perform every task by rotating through the different jobs within the team. In addition to standard functional tasks, the teams performed quality inspections and routine maintenance.

While Ohno's teams were given collective autonomy, they lacked much in the way of individual autonomy. Individual freedom of choice was limited because a team member had to gain consensus from the group before making a change. Furthermore, team members lacked individuality because they were all trained to perform the same tasks. Some people enjoy being generalists, while others prefer to specialize in a particular area. The Toyota lean production system does not allow for these individual differences in internal motivation.

Another significant issue is that the team tasks have to be limited in scope due to the finite capability for training and performing multiple tasks. If people are asked to perform too many different tasks, it is unlikely that they will be able to perform them all well. The training costs for a fully cross-trained team rapidly increase as the number of different tasks increases. The depth of expertise within a team is also reduced because team members are expected to learn all the tasks within their team. Team members can not attain the same depth of expertise possible when they focus on a narrower set of tasks. (Klein, 1993)

Small Business Teams

Janice Klein (1993) summarized STS theory as it applies to high performance work teams. These work teams, called "small business teams" (SBT's), address the shortcomings of the lean production job model. As the name implies, a key objective of the model is to encourage workers to use their skills/knowledge to manage their daily activities as if the team was their own small business. Team member responsibilities are not limited solely to functional tasks but may include managerial/administrative tasks traditionally handled by the functional support groups and supervisors. The work of an SBT can be plotted graphically as a three-dimensional cube, as shown in Figure 6.2.

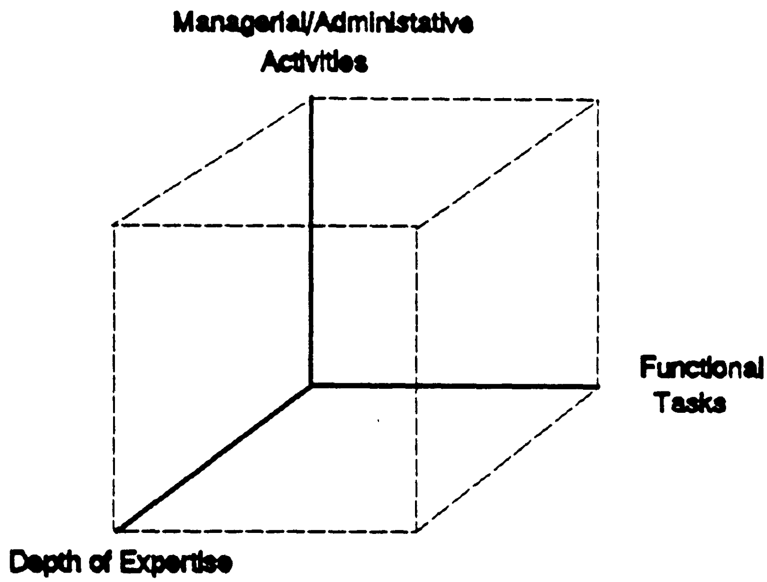


Figure 6.2 - Three dimensions of work

The horizontal axis represents the functional tasks necessary to produce the output. This would include activities such as machine setup and operation, quality inspection, and routine maintenance. Managerial/administrative activities are charted on the vertical axis and would include staffing, budgeting, scheduling and other decision making activities associated with the operation of the SBT.

Depth of expertise in the above mentioned activities is plotted on the third axis. There are several different types of expertise associated with the work of a team. Klein (1993) breaks expertise into three different categories:

1. Operational
2. Analytic
3. Integrative

Operational expertise refers to the ability to perform a given task. Traditionally, production employees possess the operational expertise. Analytic expertise refers to the understanding of the scientific principles underlying the task and the ability to solve problems. Analytic knowledge typically resides in the engineering organization or other support functions such as planning, accounting, or R & D. Integrative expertise refers to the ability to integrate across multiple tasks, a skill usually only required of managers or supervisors. Integrative ability suggests that a person could understand the impact of one decision on several different areas of the operation or could identify problems as they arise and know who to seek out for help.

It is critical for SBT's to possess all three types of expertise in order to self-manage their own operation. Many teams have been designed with functional expertise but lacked the analytic or integrative expertise necessary to manage themselves. The SBT must possess all of the relevant knowledge and expertise within the boundaries of the three-dimensional cube. A discussion of how to set the boundaries of the cube is presented in the next chapter which presents a methodology for designing SBT's.

Based on the principles of STS design, the SBT model utilizes the concept of cross-training which is an extension of the "redundancy principle." (Cherns, 1978) Since the scope of the SBT is considerably larger than that of a lean production team it is impractical to cross-train every team member for every task. Members of an SBT are *collectively* responsible for performing all of the tasks within the team boundaries. Some members of the SBT may be cross-trained to perform multiple tasks while others may retain the necessary depth of expertise for a particular task. Ideally, an SBT covers the entire cube while individual team members are capable of several tasks but maintain expertise in their chosen field. (Klein, 1993) Balancing the need for redundant skills against the costs of training is a major factor in determining the extent of multi-skilling within an SBT. A detailed description of this cost/benefit analysis is presented in the next chapter.

The SBT model balances the need for both generalists and specialists. Team members have the flexibility as in the lean production model, but also maintain expertise in specific areas. Retaining expertise within the team eliminates the time lag associated with consulting a support group to address routine operational issues. This model also provides individual team members with some degree of choice in job assignment and skill development.

The following chapter presents a structured methodology for the actual designing of an SBT for a manufacturing production group.

Chapter Seven
Small Business Team Design Methodology

The task of designing or redesigning a work system is a complex and lengthy process involving many different phases. It is especially challenging when the goal is to create some form of self-managing work team. Many researchers have been written about the process of developing self-managing work teams. (Orsburn et al., 1990; Katzenbach & Smith, 1993; Weisbord, 1987) Although the researchers may use different terms, they all describe the same basic framework for structuring a work design project. Figure 7.1 is a summary of the major phases of a work design project. The circled box, "workplace analysis and design of a new work system", is perhaps the most variable step in the process, depending entirely upon the job model that is utilized.

Figure 7.2 represents a structured methodology for performing a workplace analysis and designing a small business team (SBT) in a manufacturing production setting. Some aspects of this methodology were drawn from the literature on work design. In particular, the research on sociotechnical systems by Emery and Trist (1978) was utilized in developing this methodology. This methodology, however, is primarily based on my personal experience during the internship. It represents one of many possible ways to approach the workplace analysis and design step. The methodology presented here is meant to be used as a guideline and should be modified to fit each particular work design situation. The remainder of this chapter describes each step in the process in detail.

Step 1 - Flowchart the entire production process.

The first step in any workplace analysis is to identify and understand all of the tasks that must be performed in order to produce the product. Ideally, this step should

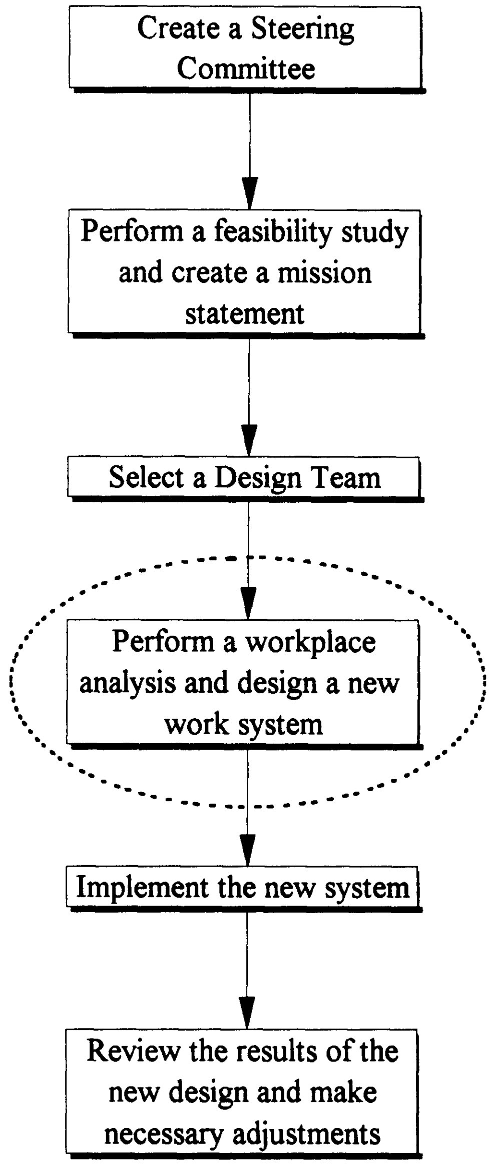


Figure 7.1 - Flowchart of typical components of work design process.

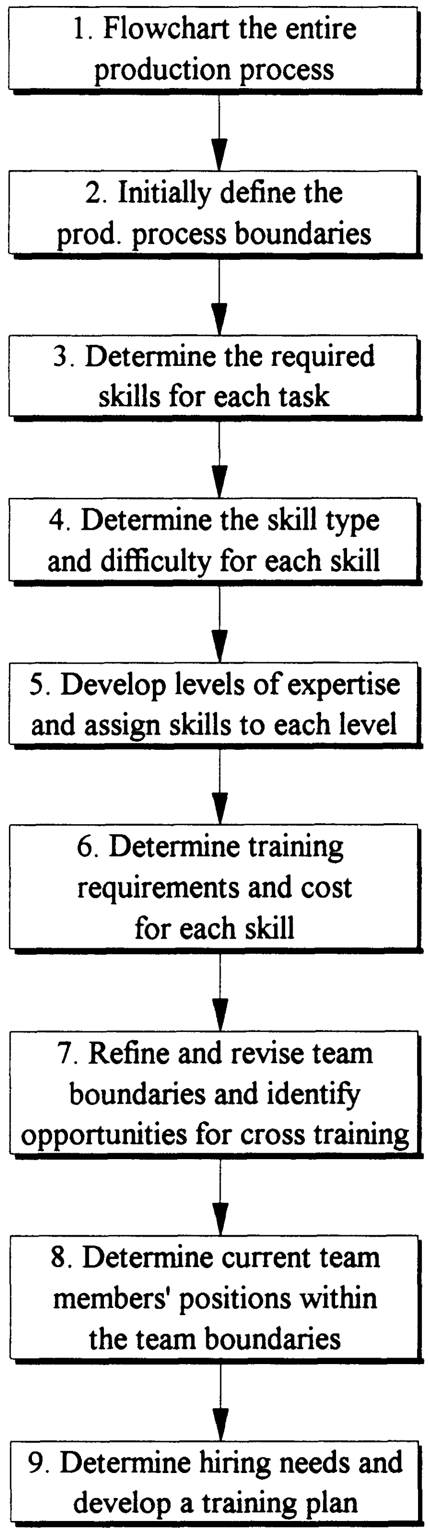


Figure 7.2 - Small Business Team Design Methodology

involve all of the people who are part of the production process. Group meetings should be scheduled to identify every task in the production process. Even though the scope of the proposed team may only encompass part of the production process it is important to document the entire process from ordering of raw materials and initiating an order all the way to shipping the finished product to stock. Opportunities to expand the scope of the team may be identified by looking at the entire production process. The flow of information should also be documented during these meetings. Understanding how information flows through the system is critical since tracking and conveying information is one of the most significant tasks that a self-managing team must undertake.

Group meetings are important because they serve to educate people about what everyone else's role is in the process. Furthermore people will gain an understanding of the whole production process, not just their own individual responsibilities. People begin to realize how critical some steps are in the process and how local control over these steps could greatly improve performance. This is particularly true for information flows. All too often people discover that information does not flow directly from step to step thus creating major delays and/or distortions in the information because it passes through too many people.

A group leader should be assigned during each meeting to coordinate the meeting and to develop the flowchart as the group describes the process. The result of these meetings will be pages of detailed flowcharts. At this point, a more general flowchart should be created that summarizes the major steps in the process.

Step 2 - Initially define the production process boundaries.

If the design team has not already determined the boundaries for the team, then it is necessary to set the boundaries at this point. While the ultimate goal is to design a team that can perform many different tasks, the group must make an initial determination of what tasks will likely be within the team's control. The design process will become overly complicated if some boundaries are not set and the group will waste time analyzing tasks that will always be beyond the comprehension of the production team. There are several different tools available to determine what tasks should be included within the team boundaries. Sociotechnical systems variance analysis as described by Emery and Trist (1978) and summarized in Chapter Six is one such tool.

Typically the interdependence of tasks or the scope of an entire process or product is used as the criterion for determining the team boundaries. For example, a production team would most likely place engineering design outside of its boundaries because an advanced degree is necessary to perform design work and because design work could be considered a separate process from production. Likewise, a machining group may choose not to incorporate a forging operation within its boundaries because the forge shop produces raw forgings for many different machining groups.

These initial boundaries for the team are not permanent. Later in the design process these boundaries will be refined and revised as more knowledge about skill level requirements and training needs is acquired.

Step 3 - Determine the skills required for each task.

Once the initial boundaries are set for the team, the group is ready to identify the skills that are required to perform each task. I recommend that group meetings be arranged based on the major steps in the summary flowchart. The people currently responsible for the tasks should be present as well as the people who may actually be in the team. This will reinforce the understanding and appreciation for other people's work that was established during the initial flowcharting meetings. Additionally, this will result in direct transfer of knowledge to the potential team members.

All of the skills necessary to perform each task should be documented. The group leader should encourage people to think not only of operational skills but analytic and integrative skills as well. Identifying the operational skills is easy, understanding what analytic abilities and integrative skills are needed to complete a task is much more challenging. The group leader may need to provide examples of analytic and integrative skills for reference purposes. Once people understand what analytic and integrative skills are they will become able to identify those types of skills for each task. The group should remember to include those skills required to handle information flows.

A spreadsheet with a listing of all of the tasks with the corresponding skills required for each task could be developed to document the work performed up to this point. A spreadsheet format provides a clear visual format that can be easily manipulated.

Step 4 - Determine the skill type and difficulty for each skill.

Once the spreadsheet of tasks and their associated skills is developed, the group should then determine the type of skill and the difficulty level for each skill. Since the definitions for each level of expertise will be based upon the type and difficulty of the acquired skills it is necessary to identify these skill characteristics. Each skill can be classified as operational, analytic, or integrative. (Klein, 1993) The skill type may have already been identified for many of the skills during the previous step, so this process should not take a long time. One should not be surprised to find that the skills currently required for a production team are primarily operational with a few analytic requirements. Traditionally, most analytic and integrative skills reside in the supervisors, managers or engineers.

The level of difficulty for each skill must also be determined. There are three different levels of difficulty: routine, advanced, and craft. A routine skill is one that might be required of every team member since it often needed and thus coverage is necessary in the event of absences. For example, all members of a machining group might be expected to be able to load and operate every machine in the group's area. Advanced skills would require more training and experience and may be what each team member aspires to. Advanced skills would not necessarily be utilized every day. The ability to perform complicated machine setups or perform trouble shooting of the machines might be considered advanced skills for a machining group. Craft level skills are only needed occasionally and require specialized training and extensive experience. Craft skills are most often located in support groups since they are not needed on a daily basis. Craft skills for a machining group might include the ability to perform electrical and mechanical repair on the machines or the ability to sharpen cutting tools. The different levels of difficulty should be explained to the group and then each skill can be ranked by consensus.

Additional columns can be added to the spreadsheet so that it includes the tasks, type of task, required skills, and skill type and difficulty. A page from a completed spreadsheet is provided in Figure 7.3 as an example of an easy-to-read format for all of the data.

Step 5 - Develop levels of expertise and assign skills to each level.

Once the various skills have been identified for the horizontal and vertical axes of the organizational cube, I recommend that the design group begin to consider the third axis, depth of expertise. Several distinct levels of expertise should be created. These levels can be thought of as progressive steps in a training program. The levels may not simply be the routine, advanced, and craft levels determined for each skill in the previous step. The levels of expertise are more general skill groupings which may not have all of the same difficulty skills in one level. For example, one level may include some routine operational skills as well as some advanced analytic skills. The difficulty level for each

Activity: Assembly & Polish

Task #	Task	Type	Necessary Skills	Skill Type
A1	Clean neck and outside rings to remove forgings lines	Func.	basic polishing skills	Routine,Operational
			knowledge of contact wheels and belts	Routine,Analytic
			knowledge of belt life and replacement needs	Routine,Analytic
			ability to shape contact wheel	Advanced,Operational
A2	Fixture parts, drill and countersink holes	Func.	operation of a drill press	Routine,Operational
			sharpening drill bits	Craft,Operational
			knowledge of speeds and feeds	Advanced,Analytic
			knowledge of drill bit wear and replacement needs	Routine,Analytic
A3	Mating surfaces of parts are glass beaded after heat treating	Func.	operation of glass beading machine	Routine,Operational
			ability to glass bead parts to uniform color	Routine,Operational
			ability to unclog glass bead hoses	Routine,Operational
A4	Neck, outside rings, and inside shanks are polished and compounded	Func.	basic polishing skills	Routine,Operational
			ability to shape contact wheel	Advanced,Operational
			knowledge of contact wheels and belts	Routine,Analytic
			knowledge of belt life and replacement needs	Routine,Analytic
			knowledge of polishing wheels, compounds and wheel life	Routine,Analytic
A5	Drill pivot hole and bend end of long ring if necessary	Func.	operation of Di-acro bending machine	Routine,Operational
			operation of comparator	Routine,Operational
			operation of drill press	Routine,Operational
			ability to straighten parts after bending	Routine,Operational
			knowledge of fixture wear and replacement needs	Advanced,Analytic

Figure 7.3 - Example of a task and skill data collection spreadsheet

skill was determined in the previous step to be used as a guideline for placement in the various expertise levels.

Three or four different levels of expertise are usually appropriate for production teams. Professional teams, such as engineering teams, may require additional levels. Before assigning skills to a particular level of expertise, the group should write down brief definitions of what a person should be able to do at each level of expertise. It is much easier to determine what skills are needed for each expertise level once these levels are clearly defined. In some cases it may be necessary to create different definitions for functional tasks and administrative tasks.

In many traditional job designs the levels of expertise are defined solely by the difficulty of operational skills. Higher levels of expertise are achieved by acquiring more advanced operational skills. In other traditional job designs the levels are based primarily on seniority which may or may not correspond to a person's ability to perform more advanced operational skills. Neither of these approaches puts much value on analytic or integrative skills and should not be used when designing an SBT. The design group has spent many hours identifying and defining the operational, analytic and integrative skills required to perform various tasks. Therefore the levels of expertise should be based on a combination of *all* three types of skills. One such approach is to create levels of expertise based on problem solving ability. At the lower levels a person can only identify problems, while at higher levels a person can diagnose problems and determine the root causes. At still higher levels, a person can also recommend corrective action and perform rework. This approach defines levels of expertise based on all of the different types of skills not simply operational skills. This approach is particularly useful for organizations in which problem solving is routinely performed.

Once the levels of expertise are clearly defined, the group can assign skills to each level. A spreadsheet can be created for each level of expertise and should contain a list of all of the skills required to achieve that level. Each skill type should be listed separately so people can easily read the operational, analytic, and integrative skills needed to achieve each level.

Step 6 - Determine training requirements and cost for each skill.

Once all three axes of the organizational cube have been identified and documented, the next step is to determine the training requirements for each skill and the cost of that training. This information is useful when the design group refines and revises the team boundaries and determines the degree of multi-skilling/cross training within the team. Additionally, for some organizations, this step will be the first time that training requirements are actually documented. Experienced workers and first-line supervisors will often keep training information to themselves in order to retain some measure of superiority. If nothing else, this step will make training information available to everyone.

As many design groups have quickly discovered, quantifying the hours of training needed to acquire a skill and the associated cost can be a very difficult process. Training usually consists of two parts: (1) actual training time with an instructor and (2) on-the-job training (learning by doing). For many skills, especially analytic and integrative skills, most of the learning occurs through repetitive experience. This experiential learning is difficult to quantify because it is not a linear process and is very dependent on the individual who is doing the learning. Furthermore, the person is actually being somewhat productive while he is learning so it is difficult to determine what the actual cost is to the company.

The first step in this difficult process is to quantify the hours of actual training time required for each skill. An average number of hours of "practice time" for an "average person" to fully obtain each skill also needs to be determined. Since the numbers generated are very subjective, I recommend that at least three different opinions of the training requirements be obtained for each skill. Typically opinions are gathered from two different operators and at least one first-line supervisor or section leader. An average of three different responses is usually a more reliable data point than one response. The design group should still be aware of the fact that these numbers are, at best, broad estimates of the training requirements and that each individual's actual training requirements may vary significantly from the average value.

It is often found that the training requirements for many of the highest level skills cannot be obtained with any reasonable degree of accuracy. However, the group should realize that these highest level skills are not realistic candidates for cross training and may even end up outside of the team boundaries. Therefore the group should not spend too much time trying to accurately gauge training requirements for those skills.

Once the training requirements are quantified, estimates of the cost to the company for this training can be made. Measuring the cost of the actual training time with an instructor is relatively straightforward. The cost is the sum of the hourly wages paid to the instructor and the student and the cost of the materials used during the training session. The hourly wages should include overhead costs like benefits. The costs may also include replacement personnel for production while the training is being performed or any overtime that is required due to the lost production time during training. If the training was performed at a class outside the company, simply use the cost of the class and the hourly wages paid to the student as the cost of the training. This piece of the training costs should be quite accurate for most organizations.

The real challenge is to estimate the cost to the company when the person is learning while performing the task. One approach is to utilize the concept of learning curves. (Nahmias, 1989) As a worker gains more experience with the requirements of a particular task, the amount of time required to perform that task will decline. Experience has shown that these learning curves are accurately represented by an exponential relationship. Let $Y(u)$ be the number of hours required to produce the uth unit. Then the learning curve is of the form:

$$Y(u) = au^{-b}$$

where a is the number of hours required to produce the first unit and b measures the rate at which the marginal production hours decline as the cumulative number of units produced increases. Traditionally, learning curves are described by the percentage decline of the labor hours required to produce item $2n$ compared to the labor hours required to produce item n. That is, an 80 percent learning curve means that the time required to produce unit $2n$ is 80 percent of the time required to produce unit n for any value of n. An 80 percent learning curve is shown in Figure 7.4.

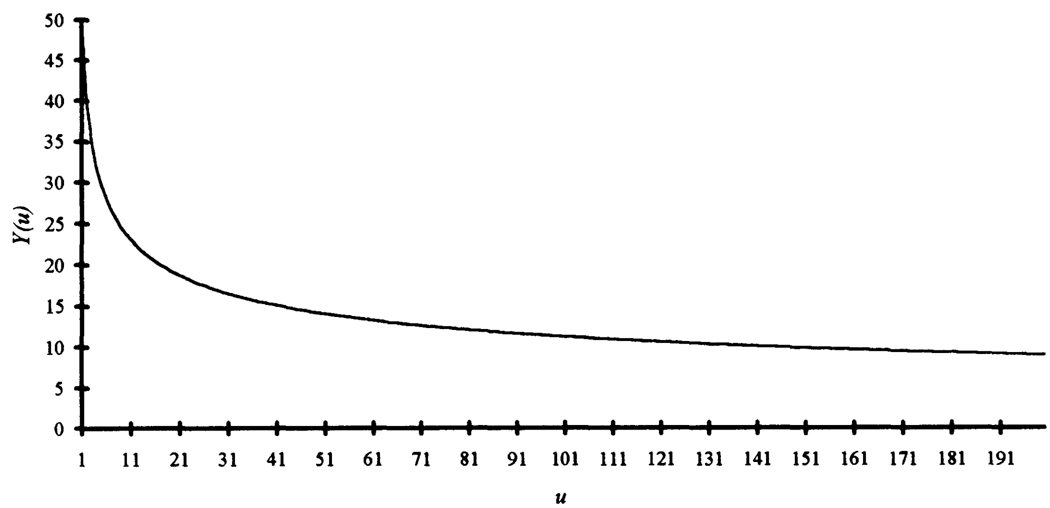


Figure 7.4 - An 80 percent learning curve

When a person is learning by experience he is actually following a learning curve. After the initial training session a person will have partially acquired a skill and thus it will take him more than the standard amount of time to complete the task. As he repeats the task over and over again, he will gradually acquire more of the skill and the time to complete the task will decline. Once he has completed the average amount of "practice time" he will have fully acquired the skill and should be able to perform the task in the standard amount of time. Since the person is actually producing product while he is practicing, the company is not paying his full hourly wages just for training. The actual cost to the company for this training time is the lost efficiency. All of the extra time beyond the standard that the person uses as he is learning is an estimate of the training cost. In reality, the person's scrap rate may also be higher during training and thus the additional scrap costs should also be included in the training cost. However, for most of the lower level skills this additional scrap cost is relatively small and can be omitted for simplicity's sake.

A visual representation of the training cost during practice is shown in Figure 7.5. The region below the learning curve and above the standard time line represents the lost efficiency and thus the cost of the training. It is a relatively simple task to actually quantify the value of the shaded region. The design group could develop a spreadsheet to input the training data and calculate the estimated cost.

The most subjective part of this learning curve estimation process is choosing the learning curve itself. An 80 percent learning curve is most often used as an average rate of learning. If the skills can be learned at a more aggressive rate, a 70 percent learning curve should be used. For more complicated skills that are learned at a slower rate, a 90 percent learning curve may be more appropriate. The design group should reach a consensus on which curve to use based on their own experiences.

In summary, the total cost of training is composed of two parts, the cost of the training session and the cost of the lost efficiency during practice. While the cost estimates generated by the process described in this step are rather broad and subjective in nature, they should at least give the design group an understanding of the relative costs of acquiring the various skills.

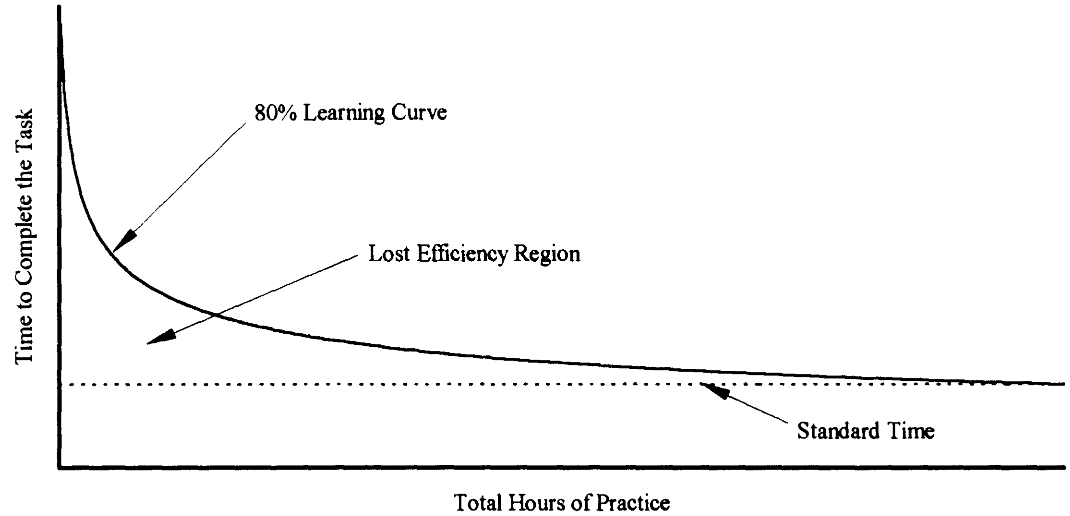


Figure 7.5 - Illustration of the lost efficiency during learning

Step 7 - Refine and revise team boundaries and identify opportunities for cross training.

Armed with the skill and task spreadsheets and the training requirements and costs data, the design group can refine and revise the team boundaries that were established at the beginning of the design process. STS variance analysis can be used once again to verify and correct the initial boundaries. Tasks that can reduce or control variances in the system should be included within the team. The design group should try to estimate the costs of not including those tasks within the team and compare them against the training costs that were estimated in the previous step. Some typical costs of excluding tasks from the team are lost production time due to information delays, increased overtime and/or rework, decreased machine utilization, and increased inventory levels. The specific costs will depend on the nature of the task itself. The design group should review the tasks that are currently near the boundaries of the team and determine the cost of not including those tasks within the team. Direct comparisons of exclusion costs and training costs will give the group some reasonably objective data for refining the team boundaries.

Once the boundaries are refined, the design group can identify opportunities for multi-skilling/cross training within the team. Routine functional and administrative skills are the most appropriate candidates for cross training because they are always needed and usually require the least amount of training. Once again, variance analysis can be used to identify the need for skill redundancy. Routine skills required to eliminate major variances are good candidates for cross training. The key criteria for determining the extent of cross training is a determination of the need for redundant skills balanced against training costs. (Klein, 1993) Cost reductions due to cross training need to be quantified. The cost reductions will depend on the specific skills and the extent of the proposed cross training. Reductions in overtime, improvements in quality, and reductions in cycle time are a few examples of the potential cost reductions due to cross training. Comparing the potential cost reduction with the training cost will help the design group determine the optimal level of cross training.

The design group should keep in mind the fact that too much cross training can be a bad thing. They should not rely completely on cost/benefit analyses to determine the extent of cross training. If cross training is too widespread, team members may constantly be rotating between jobs and may never become proficient at any skill. The learning curve analyses performed earlier could be used to determine the optimal job rotation schedule. People should not be rotated to a new job while they are still on the steep part of the learning curve. It is advisable to start the team with a relatively low level of cross training and gradually expand the skill redundancy as the team matures.

Step 8 - Determine current team members' positions within the team boundaries.

Once the boundaries of the team have been refined, it is necessary to determine to what extent the current team members possess the necessary skills. The design group should identify each team member's level of expertise in both functional and administrative tasks. Filling in the organizational cube with each individual team member's competencies creates a kind of Rubic's cube. A hypothetical team with five team members is shown in Figure 7.6. This visual representation of the team allows the design group to see the differences between team members' competencies. For example, team member E is a specialist while team member D is more of a generalist.

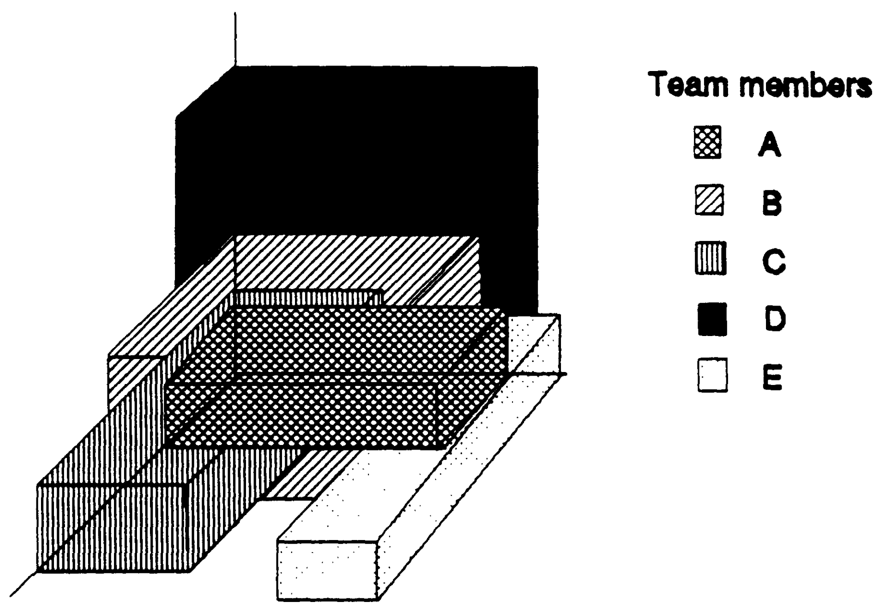


Figure 7.6 - Distribution of individual team member competencies (Klein, 1993)

Step 9 - Determine hiring needs and develop a training plan.

Once the team member competencies are mapped, it will become apparent where the gaps are within the team and where there is redundancy or flexibility of skills. The design group can then decide which gaps within the team should be filled either by training current team members or by adding new people to the team who possess the needed skills. The design group may also determine which skills need to be cross trained based on the work from the previous step. The design group can develop a hiring and training plan based on this gap analysis. At this point the work design process will shift from the workplace analysis and design phase to the implementation phase.

Final Thoughts

Although I presented the work design process as a series of discrete phases, in reality the phases overlap significantly. The structured methodology for workplace analysis and design does not abruptly end as implementation begins. In practice, the design process should continue throughout implementation in order to refine and revise the design as real life situations and problems occur.

Any organization that desires to design a new work system should keep in mind that this chapter only represents a piece of the overall process. There are many other issues besides the design of the actual work that need to be addressed. All of the organizational structures need to be redesigned as part of the work design process. As an organizational implements high performance work teams it must also change the reward systems, the compensation systems, the control system, the accountability system, and the career system. Change projects that only address the work systems frequently end in failure.

I would also like to reiterate the point made at the beginning of this chapter that it is important to conduct the workplace analysis and design in group meetings whenever possible. Involving the potential team members and the support staff in the process will build commitment and ownership of the new design and ease the difficult task of implementation. Furthermore, the people who actually perform the work are often the most capable of understanding how the work should be changed to improve performance.

The following chapter provides a case study of this workplace analysis and design process based on the small business team model. The final chapter will present some conclusions and lessons learned during the case study.

Chapter Eight
Case Study : Rongeur Cell

This chapter provides a description of a real-world attempt to perform a workplace analysis and work design based on the small business team model. The rongeur cell at Codman & Shurtleff was the focus of this case study. A description of the rongeur cell and the motivation for the study are provided in Chapter One. The experiences and results for each step in the methodology are presented in this chapter. All of the data collected in spreadsheets is presented in Appendix B.

In this case, the design group consisted essentially of one person, myself. A group was formed to help in the data collection process and to provide feedback during the design phases. The methodology presented in Chapter Seven was followed for as long as the internship lasted, about six and a half months. Given the limited manpower and the time constraint, the study did not include all nine steps in the methodology.

The Initial Meetings

The first step in the study was to establish the group that would be providing the information about the work of the team. The regular members of this group included a machinist, an assembler/polisher, the supervisor for the rongeur cell, a manufacturing engineer, and myself. Several other people, such as planners, QA inspectors, and purchasing agents were brought in for those meetings that involved their areas of expertise. It would have been too difficult to schedule weekly meeting times for a large group.

The first meeting included an explanation of the motivation for this study and a description of the methodology that would be followed. Subsequent meetings were devoted to detailed flowcharting of the rongeur production process. We started from the initial ordering of raw materials and tools and went through the steps carried out during production of forgings and machined parts. This was followed by the assembly and polish operations, the QA inspections, and finally shipment to stock. A summary flowchart of the major process steps is shown in Figure 8.1. Although the sessions started off slowly, the team members gradually warmed up to the task identification process.

The process of actually writing down all the tasks performed during production made the group realize how critical some steps are in the process and that local control of these tasks could greatly improve performance. For example, the flowchart of information flow brought to light how large the paperwork trail is and how time consuming it is to track all of the paperwork during production. The group realized that localized control of the routine paperwork could reduce the number of paperwork-related problems and thus shorten the cycle time.

Once the flowcharts were completed, the initial boundaries of the team were established. The purchasing of raw materials and the production of forgings were not included within the rongeur team. The forge shop produces forgings for many different production teams so localized control of the forging operations would not be appropriate. Raw materials were often purchased for many different products at the same time so local control of purchasing would also be difficult. The rongeur team's responsibilities would begin with the machining of parts and end with the QA inspection after final assembly. The rongeur team could assume the responsibility for quality inspections of finished rongeurs without disrupting the flow of remaining products through the QA department.

The team would also be responsible for many of the administrative tasks currently performed by the supervisor, including daily job scheduling, monitoring of the work flow, problem solving, and training of team members. The exact boundaries for the administrative tasks would be determined later on.

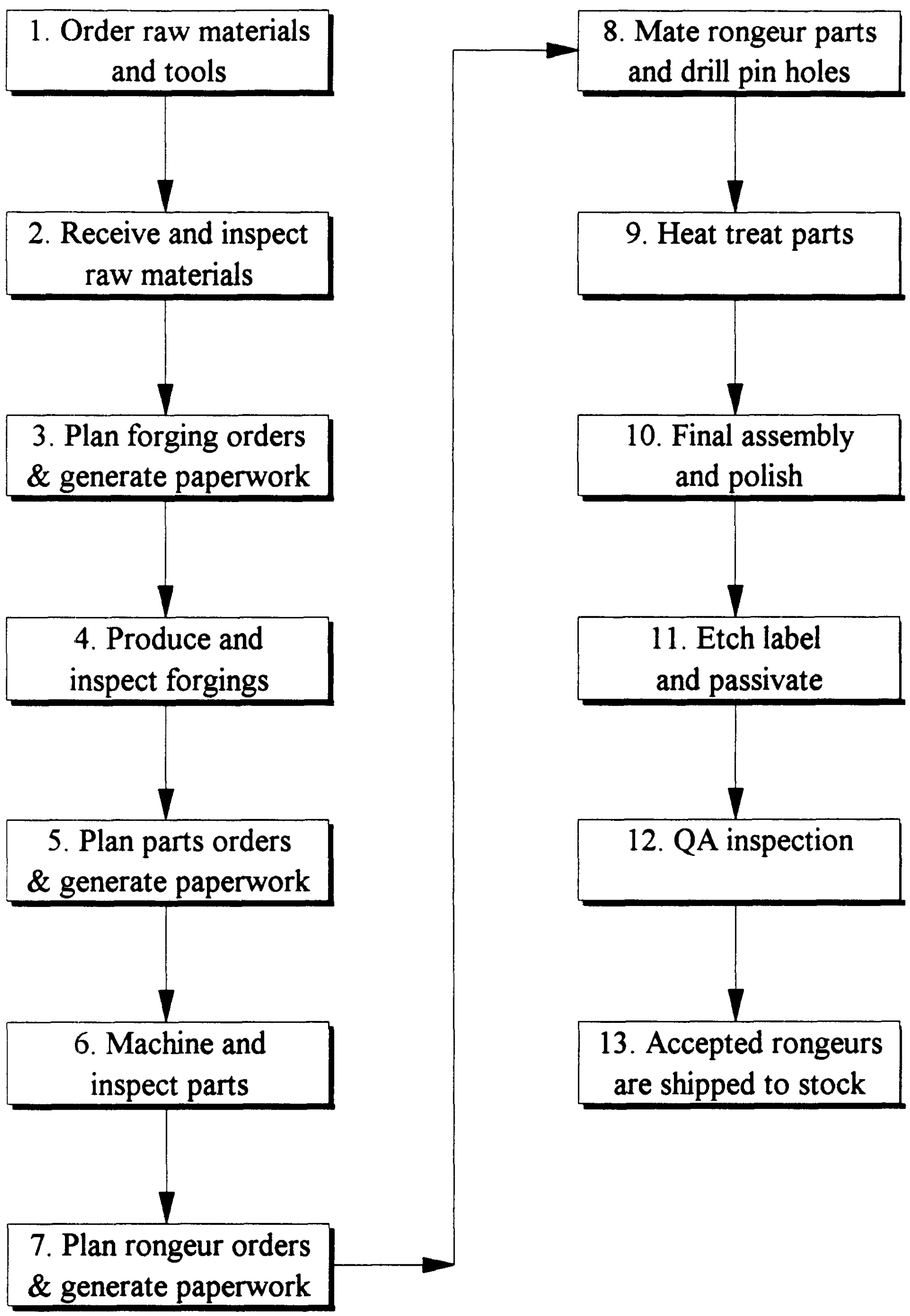


Figure 8.1 - Summary flowchart of major steps in the rongeur production process

Skill Identification Meetings

Once the team boundaries were set, the focus of the meetings shifted to identification of the skills necessary to complete each task. These meetings started with an analysis of the assembly & polish and parts machining skills since the expertise in these functional tasks resided within the current team members. The people from the support functions were then invited back to the meetings to identify the skills required for tasks in their specialties. Most of the support staff was supportive of the notion to expand the boundaries of the rongeur team to include some administrative tasks. The general attitude was that giving control of the routine administrative tasks to the team would allow the support staff to concentrate on tasks that more fully utilized their knowledge and experience. These routine administrative tasks would include daily scheduling of jobs through the department, daily production and regulatory paperwork, monitoring of work flow and expediting of backorders.

The skill type and difficulty levels were also established during these meetings. The spreadsheets that document the various tasks, their associated skills, and the skill type and difficulty are provided in Appendix B. The functional tasks were separated into several distinct groups: Parts Machining, Assembly & Polish, and QA Inspection. The various administrative tasks were all put into one category called Administration, Coordination, & Planning. The tasks were broken out into these separate groups because they require significantly different skill sets.

For most of the meetings prior to skill identification, the hourly workers' attitude had been that coming to these meetings was simply an extended coffee break. But by this point, some of the rongeur team members had become very interested in the process. For example, one machinist actually brought in machine setup sheets to describe the skills needed to setup and operate the CNC machining centers. However, others were still skeptical about the whole project. Some felt that documenting the skills and tasks required to produce a rongeur would erode their job security or reduce their stature in the team. Others did not believe that senior management was truly committed to changing the work systems. The meetings often digressed into emotional debates about management's commitment to change and whether or not this kind of change project is truly feasible at Codman.

Levels of Expertise

Once all of the task and skill data had been gathered, the levels of expertise needed to be developed. I performed this step alone since I was the entire design group for this project. Since much of the daily work in the rongeur team involved problem solving of one form or another, I decided to use the problem solving criteria outlined in Chapter Seven as a basis for developing the levels of expertise. I created different definitions for the levels of expertise for the functional and administrative tasks since they have significantly different skill sets. I developed four different levels of expertise (I-IV) for both functional and administrative tasks. (see Appendix B) Starting at the entry level (Level I) a person would progress upward through each level as his problem solving skills expanded. By the time a person reaches Level IV he can identify a problem, determine the root cause, propose a solution and perform the necessary rework.

Once the levels of expertise were established I placed the different skills into the appropriate levels. I determined which skills were needed to satisfy each expertise level definition. Since the levels were clearly defined first, this step was relatively straightforward. Once the skills were placed in the different levels, I presented the results to the group to get some feedback. Initially, some of the group members wanted to move many skills to different levels. When we began to discuss the changes it became evident to me that they were equating the new levels with the existing job levels. Once I explained that these new levels were unrelated to the existing set of job levels and required different skill sets the number of suggestions for changes decreased significantly. Most of the suggestions simply involved moving a skill up or down one level. The spreadsheets with the skill listings for each level are provided in Appendix B. The tasks required for each skill are included for reference purposes. The training requirements are also included on these spreadsheets.

Training Requirements

Just as predicted in the previous chapter, the training requirements and their associated costs were difficult to obtain with a reasonable degree of accuracy. The training requirements were broken down into the two separate pieces, actual training time and learning through practice. I arranged several small group meetings to obtain the training estimates. Whenever possible, I tried to obtain estimates from two or three people. I spoke with two supervisors and a planner about administrative tasks. I gathered data for assembly & polish from a supervisor, a polisher, and an engineer who started with the company as a polisher.

While almost everyone was in agreement on the length of the training sessions with an instructor, there was significant variation in the responses for practice time. This was particularly true for many of the higher level skills. The responses were averaged and tabulated as shown in Appendix B. If the variation was too large, I decided to leave those spots blank in the spreadsheet. If I had had more time I would have obtained additional data points to reduce the variation so I could develop more accurate average training times.

Quantifying the training needs for polishing and assembly was the most difficult step because polishing is still considered an art by many workers. The supervisor, polisher, and engineer believed that you could not quantify the training time because each individual would take a very different amount of time to master the art of polishing depending upon his inherent abilities. It took some time but I was finally able to get the group to agree on an average amount of practice time. I had to reinforce the fact that the numbers generated were estimates to be used to design a new work team and would not be used to change the time standards for polishing.

Unfortunately I did not have enough time to determine the costs of training. In addition to the time constraint, the rongeur cell was a new production group that was still "ramping up" and there wasn't any production data available for full scale production in this cell. Once some production data became available the learning curve estimates of the lost efficiency due to training could be used to estimate the cost of training. It was determined that a worker cannot perform a task at Codman until they are at least 50% efficient. Therefore each worker would receive training from an instructor until he could perform the task at 200% of the standard. The learning curve could then be used to estimate the lost efficiency as the worker progressed from 200% to 100% of the standard. If more time had been available I could have gathered production data from other production cells that perform similar operations and used it to estimate the costs of training.

Initial Design Steps and the Need for Future Work

With the majority of the workplace analysis performed the next step was to actually design the new work team structure. Unfortunately the workplace analysis had taken up most of the internship and little time remained to begin the design process. Even though a rigorous cost/benefit analysis could not be performed to determine the skills for cross training, I was able to identify some key areas that would benefit the team if they were cross trained. Most of these tasks require only level I or II skills and the team would benefit by having several people who were capable of performing them. I grouped these tasks into several general areas as follows:

- routine production paperwork
- routine operational tasks
- QA inspections - dimensional, hardness, functional, and visual
- scheduling jobs on the floor on a weekly basis
- problem identification and solving - i.e. Pareto charts, fishbone diagrams, etc.

Cross training the team in these areas would provide benefits beyond cost savings. Cross training would increase the workers level of internal motivation because their work would satisfy Hackman's core job characteristics presented in Figure 6.1 in Chapter Six. Cross training in these areas would increase the skill variety, provide a higher degree of autonomy, and provide more feedback from the job. Control over the daily paperwork and the weekly job schedule would certainly increase the team's sense of autonomy. The team would receive direct feedback from its work by performing the QA inspections. According to Hackman, satisfying these core job characteristics will lead to high internal motivation, high general job satisfaction, and high work effectiveness. Cross training would provide job enrichment for the entire team and not just the individual who is responsible for each task.

I also looked at the team boundaries that were established at the beginning of the project. Again without the aid of cost/benefit analyses I was only able to suggest a few revisions to the boundaries. The functional tasks should include Parts Machining, Assembly & Polish and gradually include QA Inspection as the team members were trained and certified as quality inspectors. The administrative task boundary should start at level I or II but may evolve to include levels III and IV skills as the team matures. The team boundaries could be more clearly defined once the cost/benefit analyses are performed and the current team members' positions in the organizational cube are determined.

One issue that was not addressed during the project was the changing role of the supervisor. As the team is trained and can become responsible for many of the supervisor's tasks, what will become of the supervisor? As the design process moves forward I think this is one key issue that must be addressed. My suggestion is that the supervisor should act as a teacher and supervisor during the transition toward a small business team. Once the team has developed sufficiently, the supervisor should become more of a facilitator and coach. The supervisor will no longer perform daily administrative tasks or solve problems. His role will be to advise the team when they need help and to facilitate communication with the support functions.

Implementation of the small business team model would also result in changes to the role of the support groups. Many of the tasks traditionally assigned to the support groups will be included within the team's boundaries. The support groups will become less involved in the daily production activities which should allow them more time to consider improvements to the system and keep up-to-date with the latest developments. The support groups will provide service to the team only when their specialized knowledge is required to solve a problem. The support groups will become suppliers of expertise to the team as opposed to active controllers of the team's daily functions. This transition in roles should be gradual and synchronized with the development of the SBT.

With some additional design work and a great deal of work in implementation, I think that the small business team model will be a good fit for the rongeur team at Codman. My experience with the current team members suggests that some people would like to remain specialists while others would prefer to become generalists. The polishers who have been with Codman for more than twenty years are generally not interested in expanding their responsibilities. However, several younger machinists expressed interest in understanding areas besides machining and would be very receptive to being cross trained in other areas. The SBT model provides a certain degree of individual team member choice in job assignment and skill development. I think the SBT model is appropriate for the rongeur cell at Codman because it would accommodate these differences in job interests within the team.

My conclusions and lessons learned from this case study are presented in the next chapter as well as some thoughts about the SBT job model itself.

Chapter Nine
Small Business Team Conclusions

Although I was not able to fully complete the workplace analysis and design during my internship at Codman, I did learn some important lessons in the process. In this final chapter I will present the lessons learned during the project, followed by some general conclusions about the small business team job model.

Lessons Learned

One of the most important lessons I learned during this project is that the work design process is very time consuming. The process appears to be relatively straightforward on paper but in reality it can be a difficult and lengthy ordeal. Unlike traditional engineering or manufacturing projects, a work design project depends almost entirely on the input from people. People are inherently more variable and unpredictable then machines and thus extracting the necessary information from people takes quite a long time. I learned that my initial expectation to perform the entire workplace analysis and design by myself in an unfamiliar organization in just six and a half months was unrealistic. The workplace analysis itself took me almost the entire six and a half months. A dedicated design group of at least three or four people with knowledge of the work design models would be needed to perform the analysis and design in just a six month period of time.

Given that this process is lengthy, its ultimate success depends heavily on the level of commitment at all levels of the organization. A work design project that aims to implement high performance work teams requires a high level of commitment from the hourly workers as well as the senior managers. People will be unwilling to change the way they do business without a strong commitment to the notion that these changes are necessary and will ultimately improve the organization. I think the commitment must be initiated by senior managers and they must foster the commitment to the project at the lower levels of the organization. Without top level commitment, people will never truly buy in to these types of change projects.

As stated in Chapter Seven, the workplace analysis and design phase is just one of several steps in the work design process. I think that the level of commitment at Codman would have been higher if I had started the project at the earlier phases of the process. A steering committee and mission statement were never created and a feasibility study was not performed prior to the workplace analysis. A higher level of commitment could have been achieved by performing these steps first and that would have made the workplace analysis and design process easier. Codman needed to become more aware of high performance work teams at all levels of the company and then identify how these teams could benefit the company. If that had been done, the motivation and commitment to actually designing the work teams would have been greater and the design process could have been more successful.

The level of interest and contribution to the work design process can vary significantly between team members and support people. Among the rongeur team members the machinists were the most interested in designing a new work system. They saw it as an opportunity to expand their own knowledge which could lead to greater job responsibility and higher pay. The polishers, generally much older than the machinists, were skeptical about the motives for changing the work systems. They feared that the work design process was just another attempt to get them to do more work for the same pay. The long-time employees were pessimistic about most change projects.

The support staff were generally interested in the new work design because they believed that it would free them from performing the routine tasks and allow them more time to do the really interesting work. Even though interest was high, the level of contribution from the support staff was generally low. Although they believed that the new work system would be beneficial, they were unwilling to spend time developing the new system because they were pessimistic about it actually being implemented. I believe that the lack of senior management commitment to the project and my own lack of authority within the company were the main reasons for the pessimism.

I also learned that the culture of an organization can greatly affect the outcome of a work design project. An in-depth understanding of the organization's culture is necessary to perform the analysis efficiently and to create an appropriate design. Had I understood Codman's culture before I started this project, I would have done things differently or at least I would have adjusted the scope of the project. For example, people at Codman will commit to attend a scheduled meeting but they often miss the meetings for a variety of reasons. The culture is such that it is generally acceptable to miss a meeting that one has previously committed to if the reason is valid. Consequently, it was very difficult to hold group meetings in which everyone attended. The entire process slowed down since it relies heavily on group meetings. I would have scheduled fewer meetings for longer time periods had I known how difficult it is to get everyone to attend.

Similar to many other organizations, Codman has a very individualistic culture. People perform most activities individually and the reward and incentive systems are primarily based on individual performance. Trying to design work systems based on teamwork and information sharing was difficult because it contradicted the established culture. As Katzenbach and Smith (1993) stated, "...long-standing habits of individualism, confusion about teams and teamwork and seemingly adverse team experiences can undermine team efforts...groups do not become teams just because we tell them to." I am not saying that work designs based on teams cannot be successful in an individualistic culture, just that an understanding of the culture is needed in order to perform the design process effectively.

One last lesson learned from the Codman project was that designing a job structure for a new team is not always easier than redesigning the work for an existing group. While many of the barriers to change aren't present in a new team, there is no performance data or experience available to analyze and improve upon. This can make it difficult to perform cost/benefit analyses for cross training and team boundary definition.

General Conclusions About Small Business Teams

Although the SBT job model can improve a group's performance, it is not an appropriate structure for all environments. In order to successfully implement the small business team structure, the team must be able to make the necessary decisions to operate within its own boundaries. This generally requires that those tasks which will directly impact another group should not be included within the team's boundaries. The team's tasks must be decoupled from the other groups. If this cannot be done, then small business teams may not be appropriate or they may have to be limited in scope. For example, teams on an assembly line are not good candidates for the SBT model because each team's tasks cannot be easily decoupled from the other teams. The SBT model would only be appropriate for an assembly line team if the tasks that were coupled to other teams were not included within the purview of the team.

At Codman, the forge shop would not be a good candidate for the SBT model because it produces forgings for many different production groups. The SBT model would only work if the scope of the team excluded tasks that would directly affect other teams. For example, scheduling of jobs through the forge shop would affect many other teams and thus it may be inappropriate to give scheduling control to the forge shop. If scheduling control was given to the forge shop, then the parameters of that scheduling control would have to be designed so that each of the internal customers' needs were satisfied.

While not explicitly mentioned before, the SBT is not a static model. (Klein, 1993) The organizational cube is merely a snapshot of an SBT at one point in time. The team boundaries can be changed as new technologies are introduced or process improvements are made. As the team matures or new members are added, the boundaries may also be changed. The SBT model may actually be used to monitor the need to change itself. This is an important feature because of the dynamic changes occurring in modern manufacturing.

At Codman the SBT model could be used to assess the need for changes in the rongeur team boundaries due to introduction of an automated surface finishing technology. The team boundaries would certainly need to be changed if centrifugal barrel finishing (CBF) was implemented to perform final polishing of the rongeurs. The team would need fewer polishing skills and would need to acquire skills in CBF machine operation and maintenance, knowledge of tumbling media, and knowledge of how cycle times affect the final surface finish. The need for additional training or new team members could easily be identified once the organizational cube has been established for the rongeur cell. This information could be used to estimate the cost of implementing the new technology and to determine the amount of time required for the implementation.

I think one dimension that is not explicitly included in the SBT model is interpersonal skills. While one could argue that they are included in administrative skills, I believe that they should be separated out in order to emphasize their importance. Just because team members are given the necessary functional and administrative skills to operate as an SBT does not imply that they will function coherently as a team. The team members must possess interpersonal skills in group dynamics, conflict resolution, communication, and group decision making. I think it is too easy to forget about these critical skills without explicitly including them in the SBT model.

Work systems based on the SBT job model are inherently complicated and cross many traditional organizational boundaries. Therefore it is critically important to change and adapt *all* of the organizational structures when implementing SBT's. Without these complementary organizational changes, any work design project is doomed to fail. Ed Schein (1992) states:

> "...if we think of cultures as interlocking sets of assumptions, what often goes wrong in organizational change programs is that we manipulate some assumptions while leaving other untouched. We create tasks that are group tasks, but we leave the reward system, the control system, the accountability system, and the career system alone. If those other systems are built on individualistic assumptions, leaders should not be surprised to discover that teamwork is undermined and subverted." (p. 140-141)

If an organization is truly committed to implementing high performance work systems than its managers must be willing to enter into a long-term relationship with its employees. In this era of corporate downsizing, I think it is important for senior executives to avoid talking out of both sides of their mouths. As Robert Kuttner (1993) recently stated, "The rush to downsize and replace longtime employees with temps and part-timers make corporate rhapsodies to empowerment, partnership, and teamwork so much sweet talk." The essence of an SBT is a commitment to training and development of the team members. Layoffs and hiring of temps is a strategy that is completely inconsistent with the SBT model and must be avoided in order to successfully implement this high performance work system.

Appendix A

Technical Cost Models for Automated Surface Finishing Technologies

Centrifugal Disc Finishing Cost Model
Codman & Shurtleff, Inc.

Model developed by John Eustis
Last revised: 1/15/94

FACTOR PRICES

Energy		
Electricity	$0.0834	$/Kwh
Process Materials		
WK,ACT,3/8"x1/4"	$0.81	$/lb.
Compound	$20.00	$/gal.
Equipment		
Rotomax RM-6A	$94,150	
Auxiliary equipment (J Press)	$5,000	
Installation cost	$1,000	
Labor		
Wage rate	$12.00	$/hour
Overhead burden rate	400%	
Total wage	$60.00	$/man-hr
Working days per year	240	
Number of shifts per day	1	
hours per shift	8	
Capital-Related Charges		
Cost of Capital (% of initial investment)	18.0%	
Insurance (% of physical equipment)	1.0%	
Maintenance (% of physical equipment)	2.0%	
Useful life of equipment	10	years
Years to Recover Investment	3	years

INPUT FACTORS

Primary Finishing Process:	Wet Cut Down of Scissors
Labor productivity	85%
Equipment working capacity	6.00 cu. ft.
Motor horsepower	10.0 hp
Motor efficiency	75%
Media wear rate	0.700 %/hour
Media density	100 lbs/cu. ft.
Compound concentration	2.0 oz/gal
Compound flow rate	10 gal/hour
Prod. volume for primary part	36,000 parts
Process time for primary part	1.00 hours/cycle
Labor content for primary part	0.300 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.50 inches
Smallest, C	0.25 inches
RV factor for primary part	0.63
Prod. volume for 2nd part	6,500 parts
Process time for 2nd part	1.00 hours/cycle
Labor content for 2nd part	0.167 hours/cycle
Dimensions - Largest, A	9.25 inches
Middle, B	3.50 inches
Smallest, C	0.25 inches
RV factor for 2nd part	0.63
Prod. volume for 3rd part	150,000 parts
Process time for 3rd part	1.00 hours/cycle
Labor content for 3rd part	0.300 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.75 inches
Smallest, C	0.20 inches
RV factor for 3rd part	0.63

PRODUCTION CALCULATIONS

Primary part		
Average rotational volume	36.53	RV/cu. ft.
Parts processed per cu. ft.	23.02	parts/cu. ft.
Parts processed per cycle	138	parts/cycle
Total cycle time	1.353	hours/cycle
Projected production hours	353	hours
2nd part		
Average rotational volume	15.07	RV/cu. ft.
Parts processed per cu. ft.	9.49	parts/cu. ft.
Parts processed per cycle	56	parts/cycle
Total cycle time	1.196	hours/cycle
Projected production hours	139	hours
3rd part		
Average rotational volume	33.10	RV/cu. ft.
Parts processed per cu. ft.	20.85	parts/cu. ft.
Parts processed per cycle	125	parts/cycle
Total cycle time	1.353	hours/cycle
Projected production hours	1,624	hours

Total production volume	192,500	parts
Total projected production hours	2,115	hours
Total available production hours	1,920	hours

The projected production hours EXCEED current capacity.

COST CALCULATIONS

Process Material Cost		
Compound usage per cycle	20.0	oz/cycle
Compound cost per cycle	$3.13	$/cycle
Compound cost per part	$0.02	$/part
Media usage per cycle	4.20	lbs/cycle
Media cost per cycle	$3.40	$/cycle
Media cost per part	$0.02	$/part
Energy Cost		
Energy usage per cycle	10.00	kwh/cycle
Energy cost per cycle	$0.83	$/cycle
Energy cost per part	$0.01	$/part
Labor Cost		
Labor content per cycle	0.353	hours/cycle
Labor cost per cycle	$21.18	$/cycle
Labor cost per part	$0.15	$/part
Equipment Cost		
Total equipment cost	$100,150	
Annual equipment cost	$10,015	$/year
Equipment cost per part	$0.05	$/part
Capital Costs		
Annual cost of capital	$12,678	$/year
Cost of capital per part	$0.06	$/part
Insurance per part	$0.00	$/part
Maintenance per part	$0.01	$/part

Cost Summary for Wet Cut Down of Scissors

Variable Cost Elements

	$/part	percent
Process material cost	$0.05	14.5%
Energy cost	$0.01	1.9%
Direct labor cost	$0.15	47.1%
TOTAL VARIABLE COST	$0.21	63.5%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.05	14.2%
Maintenance cost	$0.01	2.8%
Cost of capital	$0.06	18.0%
Insurance	$0.00	1.4%
TOTAL FIXED COST	$0.12	36.5%

	$/part	percent
TOTAL FINISHING COST	**$0.33**	**100%**

Centrifugal Barrel Finishing Cost Model
Codman & Shurtleff, Inc.

Model developed by John Eustis
Last revised: 1/15/94

FACTOR PRICES

Energy			
Electricity	$0.0834	$/Kwh	
Process Materials			
C-coarse corn cob	$0.49	$/lb.	
EC-1 compound	$19.95	$/gal.	
Equipment			
Tmesaver HZ-120 CBF	$29,950		
Auxiliary equipment	$5,000		
Installation cost	$1,000		
Labor			
Wage rate	$12.00	$/hour	
Overhead burden rate	400%		
Total wage	$60.00	$/man-hr	
Working days per year	240		
Number of shifts per day	1		
hours per shift	8		
Capital-Related Charges			
Cost of Capital (% of initial investment)		18.0%	
Insurance (% of physical equipment)		1.0%	
Maintenance (% of physical equipment)		2.0%	
Useful life of equipment		10	years
Years to Recover Investment		3	years

INPUT FACTORS

Primary Finishing Process:	Dry tumbling of IVD rongeurs
Wet(1) or dry(0) processing?	0
Labor productivity	85%
Total volume of machine	3.8 cu. ft.
Number of barrels	4
Motor horsepower	10.0 hp
Motor efficiency	80%
Barrel fill percentage	85%
Media life	12 number of cycles
Media density	33 lbs/cu. ft.
Compound usage per cycle	8.0 oz/gal
Prod. volume for primary part	6,500 parts
Process time for primary part	1.00 hours/cycle
Labor content for primary part	0.250 hours/cycle
Dimensions - Largest, A	9.50 inches
Middle, B	3.75 inches
Smallest, C	0.20 inches
RV factor for primary part	0.50
Prod. volume for 2nd part	6,000 parts
Process time for 2nd part	0.50 hours/cycle
Labor content for 2nd part	0.250 hours/cycle
Dimensions - Largest, A	0.67 inches
Middle, B	0.20 inches
Smallest, C	0.20 inches
RV factor for 2nd part	0.40
Prod. volume for 3rd part	10,000 parts
Process time for 3rd part	0.50 hours/cycle
Labor content for 3rd part	0.250 hours/cycle
Dimensions - Largest, A	2.00 inches
Middle, B	0.30 inches
Smallest, C	0.30 inches
RV factor for 3rd part	0.40

PRODUCTION CALCULATIONS

Equipment working capacity	3.23 cu. ft.
Primary part	
Average rotational volume	13.38 RV/cu. ft.
Parts processed per cu. ft.	6.69 parts/cu. ft.
Parts processed per cycle	21 parts/cycle
Parts per barrel	5 parts/barrel-cycle
Total cycle time	1.294 hours/cycle
Projected production hours	401 hours
2nd part	
Average rotational volume	26489.00 RV/cu. ft.
Parts processed per cu. ft.	10595.60 parts/cu. ft.
Parts processed per cycle	34223 parts/cycle
Total cycle time	0.794 hours/cycle
Projected production hours	0 hours
3rd part	
Average rotational volume	2345.42 RV/cu. ft.
Parts processed per cu. ft.	938.17 parts/cu. ft.
Parts processed per cycle	3030 parts/cycle
Total cycle time	0.794 hours/cycle
Projected production hours	3 hours

Total production volume	22,500 parts
Total projected production hours	403 hours
Total available production hours	1,920 hours

The projected production hours are within current capacity.

COST CALCULATIONS

Process Material Cost		
Compound usage per cycle	8.0	oz/cycle
Compound cost per cycle	$1.25	$/cycle
Compound cost per part	$0.06	$/part
Media usage per cycle	8.88	lbs/cycle
Media cost per cycle	$4.35	$/cycle
Media cost per part	$0.21	$/part
Energy Cost		
Energy usage per cycle	9.38	kwh/cycle
Energy cost per cycle	$0.78	$/cycle
Energy cost per part	$0.04	$/part
Labor Cost		
Labor content per cycle	0.294	hours/cycle
Labor cost per cycle	$17.65	$/cycle
Labor cost per part	$0.84	$/part
Equipment Cost		
Total equipment cost	$30,950	
Annual equipment cost	$3,095	$/year
Equipment cost per part	$0.47	$/part
Capital Costs		
Annual cost of capital	$3,918	$/year
Cost of capital per part	$0.60	$/part
Insurance per part	$0.05	$/part
Maintenance per part	$0.09	$/part

Cost Summary for Dry tumbling of IVD rongeurs

Variable Cost Elements

	$/part	percent
Process material cost	$0.27	11.3%
Energy cost	$0.04	1.6%
Direct labor cost	$0.84	35.7%
TOTAL VARIABLE COST	$1.14	48.6%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.47	20.1%
Maintenance cost	$0.09	3.9%
Cost of capital	$0.60	25.4%
Insurance	$0.05	1.9%
TOTAL FIXED COST	$1.21	51.4%

	$/part	percent
TOTAL FINISHING COST	**$2.35**	**100%**

Vibratory Tumbling Cost Model
Codman & Shurtleff, Inc.

Model developed by John Eustis
Last revised: 1/15/94

FACTOR PRICES

Energy		
Electricity	$0.0834	$/Kwh
Process Materials		
D40,ACS,1-3/8"x1/2"	$1.04	$/lb.
Compound	$20.00	$/gal.
Equipment		
Round vibratory bowl	$1,000	(salvage value)
Auxiliary equipment (J Press)	$5,000	
Installation cost	$	
Labor		
Wage rate	$12.00	$/hour
Overhead burden rate	400%	
Total wage	$60.00	$/man-hr
Working days per year	240	
Number of shifts per day	1	
hours per shift	8	

Capital-Related Charges		
Cost of Capital (% of initial investment)	18.0%	
Insurance (% of physical equipment)	1.0%	
Maintenance (% of physical equipment)	4.0%	
Useful life of equipment	10	years
Years to Recover Investment	3	years

INPUT FACTORS

Primary Finishing Process:	Wet Cut Down of Scissors
Labor productivity	85%
Inside diameter of vibrator channel	13.25 inches
Outside diameter of center section	17.00 inches
Motor horsepower	5.0 hp
Motor efficiency	75%
Media wear rate	1.100 %/hour
Media density	95 lbs/cu. ft.
Compound concentration	0.0 oz/gal
Compound flow rate	0 gal/hour
Prod. volume for primary part	36,000 parts
Process time for primary part	3.00 hours/cycle
Labor content for primary part	0.500 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.30 inches
Smallest, C	0.25 inches
RV factor for primary part	0.63
Prod. volume for 2nd part	6,500 parts
Process time for 2nd part	3.00 hours/cycle
Labor content for 2nd part	0.333 hours/cycle
Dimensions - Largest, A	9.25 inches
Middle, B	3.75 inches
Smallest, C	0.25 inches
RV factor for 2nd part	0.63
Prod. volume for 3rd part	1,000 parts
Process time for 3rd part	3.00 hours/cycle
Labor content for 3rd part	0.500 hours/cycle
Dimensions - Largest, A	7.00 inches
Middle, B	2.50 inches
Smallest, C	0.25 inches
RV factor for 3rd part	0.63

PRODUCTION CALCULATIONS

Equipment working capacity	6.83 cu. ft.
Primary part	
Average rotational volume	40.27 RV/cu. ft.
Parts processed per cu. ft.	25.37 parts/cu. ft.
Parts processed per cycle	173 parts/cycle
Total cycle time	3.588 hours/cycle
Projected production hours	747 hours
2nd part	
Average rotational volume	13.85 RV/cu. ft.
Parts processed per cu. ft.	8.72 parts/cu. ft.
Parts processed per cycle	59 parts/cycle
Total cycle time	3.392 hours/cycle
Projected production hours	374 hours
3rd part	
Average rotational volume	36.53 RV/cu. ft.
Parts processed per cu. ft.	23.02 parts/cu. ft.
Parts processed per cycle	157 parts/cycle
Total cycle time	3.588 hours/cycle
Projected production hours	23 hours
Total production volume	43,500 parts
Total projected production hours	1,143 hours
Total available production hours	1,920 hours

The projected production hours are within current capacity.

COST CALCULATIONS

Process Material Cost		
Compound usage per cycle	0.0	oz/cycle
Compound cost per cycle	$0.00	$/cycle
Compound cost per part	$0.00	$/part
Media usage per cycle	21.40	lbs/cycle
Media cost per cycle	$22.26	$/cycle
Media cost per part	$0.13	$/part
Energy Cost		
Energy usage per cycle	15.00	kwh/cycle
Energy cost per cycle	$1.25	$/cycle
Energy cost per part	$0.01	$/part
Labor Cost		
Labor content per cycle	0.588	hours/cycle
Labor cost per cycle	$35.29	$/cycle
Labor cost per part	$0.20	$/part
Equipment Cost		
Total equipment cost	$6,000	
Annual equipment cost	$600	$/year
Equipment cost per part	$0.01	$/part
Capital Costs		
Annual cost of capital	$760	$/year
Cost of capital per part	$0.01	$/part
Insurance per part	$0.00	$/part
Maintenance per part	$0.00	$/part

Cost Summary for Wet Cut Down of Scissors

Variable Cost Elements

	$/part	percent
Process material cost	$0.13	34.8%
Energy cost	$0.01	2.0%
Direct labor cost	$0.20	55.1%
TOTAL VARIABLE COST	$0.34	91.9%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.01	2.9%
Maintenance cost	$0.00	1.2%
Cost of capital	$0.01	3.7%
Insurance	$0.00	0.3%
TOTAL FIXED COST	$0.03	8.1%

	$/part	percent
TOTAL FINISHING COST	**$0.37**	**100%**

Burlytic Processing Cost Model
Codman & Shurtleff, Inc.

Model developed by John Eustis
Last revised: 1/15/94

FACTOR PRICES

Energy		
Electricity	$0.0834	$/Kwh
Process Materials		
Burlyte electrolyte	$35.00	$/gal.
Equipment		
500 amp Burlytic equipment	$174,912	
25 gal/day distillation unit	$9,850	
Installation cost	$1,500	
Labor		
Wage rate	$12.00	$/hour
Overhead burden rate	400%	
Total wage	$60.00	$/man-hr
Working days per year	240	
Number of shifts per day	1	
hours per shift	8	

Capital-Related Charges		
Cost of Capital (% of initial investment)	18.0%	
Insurance (% of physical equipment)	1.0%	
Maintenance (yearly cost)	$3,500	
Useful life of equipment	20	years
Years to Recover Investment	3	years

INPUT FACTORS

Primary Finishing Process:	bright polishing of scissor rings
Labor productivity	85%
Normal power loading	19.0 KVA
Electrolyte usage	110.0 gal/year
Sludge generation	3.0 gal/week
Sludge disposal cost	$16.50 $/gal
Prod. volume for primary part	36,000 parts
Process time for primary part	3.0 minutes/cycle
Labor content for primary part	3.0 minutes/cycle
Parts processed per cycle	12 parts/cycle
Prod. volume for 2nd part	100,000 parts
Process time for 2nd part	3.0 minutes/cycle
Labor content for 2nd part	3.0 minutes/cycle
Parts processed per cycle	10 parts/cycle
Prod. volume for 3rd part	20,000 parts
Process time for 3rd part	3.0 minutes/cycle
Labor content for 3rd part	3.0 minutes/cycle
Parts processed per cycle	12 parts/cycle

PRODUCTION CALCULATIONS

Primary part	
Total cycle time	0.059 hours/cycle
Projected production hours	176 hours
2nd part	
Total cycle time	0.059 hours/cycle
Projected production hours	588 hours
3rd part	
Total cycle time	0.059 hours/cycle
Projected production hours	98 hours
Total production volume	156,000 parts
Total projected production hours	863 hours
Total available production hours	1,920 hours

The projected production hours are within current capacity.

COST CALCULATIONS

Process Material Cost		
Electrolyte cost per part	$0.02	$/part
Energy Cost		
Energy usage per cycle	0.95	kwh/cycle
Energy cost per cycle	$0.08	$/cycle
Energy cost per part	$0.01	$/part
Labor Cost		
Labor content per cycle	0.059	hours/cycle
Labor cost per cycle	$3.53	$/cycle
Labor cost per part	$0.29	$/part
Sludge Disposal Cost		
Sludge generation per part	0.001	gal/part
Sludge disposal cost per part	$0.02	$/part
Equipment Cost		
Total equipment cost	$186,262	
Annual equipment cost	$9,313	$/year
Equipment cost per part	$0.05	$/part
Capital Costs		
Annual cost of capital	$23,579	$/year
Cost of capital per part	$0.13	$/part
Insurance per part	$0.01	$/part
Maintenance per part	$0.02	$/part

Cost Summary for bright polishing of scissor rings

Variable Cost Elements

	$/part	percent
Process material cost	$0.02	4.4%
Energy cost	$0.01	1.2%
Sludge disposal cost	$0.02	2.7%
Direct labor cost	$0.29	52.7%
TOTAL VARIABLE COST	$0.34	61.1%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.05	9.5%
Maintenance cost	$0.02	3.6%
Cost of capital	$0.13	24.0%
Insurance	$0.01	1.9%
TOTAL FIXED COST	$0.22	38.9%

	$/part	percent
TOTAL FINISHING COST	**$0.56**	**100%**

Manual Finishing Cost Model
Codman & Shurtleff, Inc.

Model developed by John Eustis
Last revised: 1/15/94

FACTOR PRICES

Energy		
Electricity	$0.0834	$/Kwh
Process Materials		
220J grit grinding belts	$2.93	each
Norton finishing wheels	$92.52	each
Equipment		
Grinding machine	$0	(salvage value)
Finishing lathe	$0	(salvage value)
Installation cost	$0	
Labor		
Wage rate	$12.00	$/hour
Overhead burden rate	400%	
Total wage	$60.00	$/man-hr
Working days per year	240	
Number of shifts per day	1	
hours per shift	8	
Capital-Related Charges		
Cost of Capital (% of initial investment)	18.0%	
Insurance (% of physical equipment)	1.0%	
Maintenance (yearly cost)	$200	$/year
Useful life of equipment	10	years
Years to Recover Investment	3	years

INPUT FACTORS

Finishing Process:	Hand polishing of IVD rongeurs
Labor productivity	85%
Total production volume	6,500 parts
Belt grinder horsepower	2.0 hp
Motor efficiency	75%
Finishing lathe horsepower	2.0 hp
Motor efficiency	75%
Grinding cycle time	0.055 hours/part
Finishing cycle time	0.067 hours/part
Average 220 grit belt life	30 parts/belt
Average Scotch-Brite wheel life	750 parts/wheel

COST CALCULATIONS

Production Calculations	
Total available production hours	1,920 hours/person
Total cycle time	0.144 hours/cycle
Product production hours	933 hours
Process Material Cost	
220 grit belt cost per part	$0.10 $/part
Scotch-Brite wheel cost per part	$0.12 $/part
Energy Cost	
Energy usage per part	0.29 kwh/part
Energy cost per part	$0.02 $/part
Labor Cost	
Labor content per part	0.144 hours/part
Labor cost per part	$8.61 $/part
Equipment Cost	
Total equipment cost	$0
Annual equipment cost	$0 $/year
Equipment cost per part	$0.00 $/part
Capital Costs	
Annual cost of capital	$0 $/year
Cost of capital per part	$0.00 $/part
Insurance per part	$0.00 $/part
Maintenance per part	$0.03 $/part

Cost Summary for Hand polishing of IVD rongeurs

Variable Cost Elements

	$/part	percent
Process material cost	$0.22	2.5%
Energy cost	$0.02	0.3%
Direct labor cost	$8.61	96.9%
TOTAL VARIABLE COST	$8.86	99.7%

Fixed Cost Elements

	$/part	percent
Equipment cost	$0.00	0.0%
Maintenance cost	$0.03	0.3%
Cost of capital	$0.00	0.0%
Insurance	$0.00	0.0%
TOTAL FIXED COST	$0.03	0.3%

	$/part	percent
TOTAL FINISHING COST	**$8.89**	**100%**

Appendix B

SBT Data Spreadsheets for Rongeur Cell

Activity: Assembly & Polish

Task #	Task	Type	Necessary Skills	Skill Type
A1	Clean neck and outside rings to remove forgings lines	Func.	basic polishing skills	Routine,Operational
			knowledge of contact wheels and belts	Routine,Analytic
			knowledge of belt life and replacement needs	Routine,Analytic
			ability to shape contact wheel	Advanced,Operational
A2	Fixture parts, drill and countersink holes	Func.	operation of a drill press	Routine,Operational
			sharpening drill bits	Craft,Operational
			knowledge of speeds and feeds	Advanced,Analytic
			knowledge of drill bit wear and replacement needs	Routine,Analytic
A3	Mating surfaces of parts are glass beaded after heat treating	Func.	operation of glass beading machine	Routine,Operational
			ability to glass bead parts to uniform color	Routine,Operational
			ability to unclog glass bead hoses	Routine,Operational
A4	Neck, outside rings, and inside shanks are polished and compounded	Func.	basic polishing skills	Routine,Operational
			ability to shape contact wheel	Advanced,Operational
			knowledge of contact wheels and belts	Routine,Analytic
			knowledge of belt life and replacement needs	Routine,Analytic
			knowledge of polishing wheels, compounds and wheel life	Routine,Analytic
A5	Drill pivot hole and bend end of long ring if necessary	Func.	operation of Di-acro bending machine	Routine,Operational
			operation of comparator	Routine,Operational
			operation of drill press	Routine,Operational
			ability to straighten parts after bending	Routine,Operational
			knowledge of fixture wear and replacement needs	Advanced,Analytic
A6	Parts are assembled and pins are riveted	Func.	operation of riveting machine	Advanced,Operational
			good hand-eye coordination for riveting small pins	Advanced,Operational
			knowledge of how pin size and length affect quality of riveting operation	Advanced,Analytic
			ability to diagnose problems	Advanced,Analytic
			ability to idenitfy root cause(s)	Advanced,Analytic
			knowledge of rework/adjustment techniques	Advanced,Analytic

Activity: Assembly & Polish

Task #	Task	Type	Necessary Skills	Skill Type
A7	Rongeur is shaped, polished and compounded	Func.	advanced polishing skills - polishing to tight tolerances with consistently uniform tapers and shapes	Advanced,Operational
			ability to use "go-no go" gages	Routine,Operational
			ability to use vernier calipers	Routine,Operational
			ability to read and write English	Routine,Operational
			ability to read and understand a blueprint	Routine,Operational
			ability to shape contact wheel	Advanced,Operational
			knowledge of contact wheels and belts	Routine,Analytic
			knowledge of belt life and replacement needs	Routine,Analytic
			knowledge of polishing wheels, compounds and wheel life	Routine,Analytic
			calibration of "go-no go" gages	Craft,Operational
			ability to diagnose problems	Advanced,Analytic
			ability to idenitfy root cause(s)	Advanced,Analytic
			knowledge of rework/adjustment techniques	Advanced,Analytic
A8	Rongeur is functionally tested and visually inspected	Func.	ability to inspect & determine "feel" of instrument	Routine,Operational
			functional inspection, diagnosis of problems, and knowledge of rework/adjustment techniques	Advanced,Analytic
A9	Maintenance of grinding and polishing machines	Func.	ability to change worn wheels and belts	Advanced,Operational
			reshaping polishing wheels when out of balance	Advanced,Operational

Activity: Parts Machining

Task #	Task	Type	Necessary Skills	Skill Type
M1	Plates are tack welded together	Func.	operation of heli-arc welding machine	Advanced,Operational
M2	Set up jobs on wire EDM machine	Func.	knowledge of EDM operating parameters and how to adjust them during setups	Routine,Analytic
			operation of wire EDM machine including changing the wire	Routine,Operational
			ability to identify problems	Routine,Analytic
			ability to read and understand detailed blueprints	Routine,Operational
M3	Wire EDM parts out of the plates	Func.	operation of wire EDM machine including changing the wire	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
M4	Operation of horizontal and CNC milling machines	Func.	ability to read and write English	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
			understanding of basic math formulas	Routine,Analytic
			operation of all measurement tools and devices	Routine,Operational
			ability to operate CNC machine controls	Routine,Operational
			ability to make tooling offsets	Routine,Operational
			knowledge of tool wear characteristics and replacement needs	Advanced,Analytic
			knowledge of fixture wear and replacement needs	Advanced,Analytic

Activity: Parts Machining

Task #	Task	Type	Necessary Skills	Skill Type
M5	Set up horizontal and CNC milling machines	Func.	ability to read and write English	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
			understanding of basic math formulas	Routine,Analytic
			operation of all measurement tools and devices	Routine,Operational
			ability to operate CNC machine controls	Routine,Operational
			knowledge of CNC programming	Advanced,Analytic
			basic knowledge of tools	Routine,Operational
			ability to make tooling offsets	Routine,Operational
			knowledge of speeds and feeds for milling	Routine,Analytic
			knowledge of tool wear characteristics and replacement needs	Advanced,Analytic
			ability to identify problems	Routine,Analytic
			ability to diagnose and make corrections until acceptable parts are achieved	Advanced,Analytic
			knowledge of surface finishes and how tool action affects the finish	Advanced,Analytic
			knowledge of fixture wear and replacement needs	Advanced,Analytic
			ability to sharpen tools	Craft,Operational
M6	Measurement and inspection of parts and SPC	Func.	ability to read and write English	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
			understanding of basic math formulas	Routine,Analytic
			operation of all measurement tools and devices	Routine,Operational
			ability to correctly remove burrs when necessary	Routine,Operational
			basic data entry and computer manipulation	Advanced,Operational
			calibration of all measurement equipment	Craft,Operational
			basic knowledge of SPC	Advanced,Analytic
M7	Maintenance of wire EDM machine and milling machines	Func.	knowledge of routine maintenance requirements	Routine,Analytic
			ability to change and/or clean water and air filters	Advanced,Operational
			ability to replenish way lube in all machines	Advanced,Operational
			ability to change out water or coolant as needed	Advanced,Operational

Activity: QA Inspection

Task #	Task	Type	Necessary Skills	Skill Type
Q1	Prerequisite skills	Admin.	ability to read and write English	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
			ability to follow guidelines & established methods	Routine,Operational
			must be a responsible, detail-oriented person	Routine,Operational
Q2	Development of a QA checklist	Admin.	knowledge of department's manufacturing processes	Craft,Integrative
			knowledge of intended use for instrument	Routine,Analytic
			knowledge of similar products	Advanced,Integrative
			knowledge of inspection techniques	Routine,Operational
			knowledge of sampling rules	Routine,Analytic
			knowledge of standard test procedures, test methods, COP's, etc.	Routine,Integrative
Q3	Inspection of paperwork	Func.	knowledge of product codes, lot numbering, and material traceability	Routine,Operational
Q4	Visual inspection - check for flaws, nicks, cracks, burrs, blemishes, correct marking, etc.	Func.	knowledge of intended use for instrument	Routine,Analytic
			knowledge of standard test procedures, test methods, COP's, etc.	Routine,Integrative
			ability to properly identify rejectable flaws	Routine,Operational
			knowing when to get a second opinion before accepting or rejecting	Routine,Integrative
Q5	Functional inspection (includes hardness testing)	Func.	knowledge of intended use for instrument	Routine,Analytic
			knowledge of standard test procedures, test methods, COP's, etc.	Routine,Integrative
			operation of hardness tester	Routine,Operational
			knowing when to get a second opinion before accepting or rejecting	Routine,Integrative

Activity: QA Inspection

Task #	Task	Type	Necessary Skills	Skill Type
Q6	Dimensional inspection	Func.	knowledge of intended use for instrument	Routine,Analytic
			knowledge of standard test procedures, test methods, COP's, etc.	Routine,Integrative
			operation of all measurement tools and devices	Routine,Operational
			knowing when to get a second opinion before accepting or rejecting	Routine,Integrative
Q7	Filling out paperwork and entering data into the computer	Admin.	basic data entry and computer manipulation	Routine,Operational
			knowledge of standard test procedures, test methods, COP's, etc.	Routine,Integrative
Q8	Inspection of reworked instruments	Func.	knowledge of how rework could have affected the instruments	Advanced,Analytic

Activity: Administration, Coordination, & Planning

Task #	Task	Type	Necessary Skills	Skill Type
C1	Prerequisite skills	Admin.	ability to read and write English	Routine,Operational
			ability to read and understand detailed blueprints	Routine,Operational
			understanding of basic mathematics formulas	Routine,Operational
			ability to operate standard computer software packages	Routine,Operational
			knowledge of accounting systems, Codman procedures, GMPs, operating procedures, etc.	Routine,Integrative
			knowledge of job levels and required skills	Routine,Integrative
			knowledge of compensation plan	Routine,Integrative
			"people" skills	Routine,Operational
			- ability to listen	
			- ability to ask the right questions	
			- trust of fellow associates	
			- ability to balance personal & professional needs	
C2	Investigate QA non-conformance reports and determine corrective actions	Func.	understanding of functional tasks	Routine,Integrative
			knowledge of intended use for instrument	Routine,Analytic
			knowledge of potential rework actions	Advanced,Analytic
			ability to consult with production staff and support groups to solve problems	Advanced,Integrative
			ability to identify problems	Routine,Analytic
			ability to identify root causes and develop solutions	Advanced,Analytic
			ability to document corrective actions	Routine,Operational
C3	Investigate and solve manufacturing problems	Func.	understanding of functional tasks	Routine,Integrative
			knowledge of intended use for instrument	Routine,Analytic
			knowledge of potential rework actions	Advanced,Analytic
			ability to consult with production staff and support groups to solve problems	Advanced,Integrative
			ability to identify problems	Routine,Analytic
			ability to identify root causes and develop solutions	Advanced,Analytic

Activity: Administration, Coordination, & Planning

Task #	Task	Type	Necessary Skills	Skill Type
C3 con't.	Investigate and solve manufacturing problems (con't.)		ability to determine which problems require corrective action	Routine,Analytic
			ability to document corrective actions	Routine,Operational
C4	Obtain weekly schedule from planner and schedule jobs on the floor	Admin.	ability to balance and manage the work force schedule to meet business objectives	Craft,Integrative
			understanding of business objectives	Advanced,Integrative
			knowledge of setups, processing times, and sequences	Routine,Integrative
			knowledge of associates' strengths and weaknesses	Advanced,Analytic
			understanding of skills required to perform tasks	Routine,Analytic
			knowledge of backorders and job priorities	Advanced,Integrative
C5	Review efficiency data, identify problem operations or people and take corrective action	Admin.	understanding of functional tasks	Routine,Integrative
			knowledge of associates' strengths and weaknesses	Advanced,Analytic
			understanding of skills required to perform tasks	Routine,Analytic
			ability to consult with production staff and support groups to solve problems	Advanced,Integrative
			ability to identify root causes and develop solutions	Advanced,Analytic
C6	Monitor work flow through the dep't and expedite backorders	Admin.	knowledge of backorders and job priorities	Advanced,Integrative
			ability to balance and manage the work force schedule to meet business objectives	Craft,Integrative
			understanding of business objectives	Advanced,Integrative
			knowledge of work flow through department	Routine,Integrative
			understanding of skills required to perform tasks	Routine,Analytic
			ability to identify bottleneck operations	Routine,Analytic
C7	Develop and execute training programs	Admin.	understanding of functional tasks	Routine,Integrative
			knowledge of associates' strengths and weaknesses	Advanced,Analytic
			understanding of skills required to perform tasks	Routine,Analytic
			ability to identify training needs within the dep't	Advanced,Integrative
			understanding of training required to develop each skill	Advanced,Analytic

Activity: Administration, Coordination, & Planning

Task #	Task	Type	Necessary Skills	Skill Type
C8	Identify and correct safety hazards	Admin.	knowledge of OSHA & Codman safety regulations	Routine,Integrative
			knowledge of who to contact for corrective action	Routine,Integrative
C9	Perform associate evaluations	Admin.	knowledge of associates' strengths and weaknesses	Advanced,Analytic
			ability to identify associates' performance levels	Advanced,Integrative
			ability to evaluate/distribute compensation fairly	Advanced,Integrative
C10	Investigate customer complaints and write reports	Admin.	understanding of functional tasks	Routine,Integrative
			knowledge of intended use for instrument	Routine,Analytic
			ability to consult with production staff and support groups to solve problems	Advanced,Integrative
			ability to identify root causes and develop solutions	Advanced,Analytic
			ability to document corrective actions	Routine,Operational
C11	Write weekly efficiency reports and track attendance and vacations	Admin.	knowledge of backorders and job priorities	Advanced,Integrative
			knowledge of associates' strengths and weaknesses	Advanced,Analytic
			understanding of skills required to perform tasks	Routine,Analytic
C12	Attend MRB meetings to explain non-conformance reports	Admin.	ability to present and explain results of an investigation to a group	Advanced,Operational
C13	Address equipment issues raised by department associates	Admin.	understanding of functional tasks	Routine,Integrative
			ability to consult with production staff and support groups to solve problems	Advanced,Integrative
			ability to identify root causes and develop solutions	Advanced,Analytic
			knowledge of what tasks the equipment perform	Routine,Integrative
C14	Create 8-week production schedule	Admin.	ability to balance and manage the work force schedule to meet business objectives	Craft,Integrative
			working knowledge of MAC-PAC system	Advanced,Operational
			knowledge of backorders and job priorities	Advanced,Integrative
			understanding of business objectives	Advanced,Integrative

Levels of Expertise for Functional Tasks

Level I

Person is able to perform routine operational tasks and basic analytical tasks such as knowing when a tool or belt is worn out and needs to be changed.

Level II

In addition to level I skills, the person is able to perform advanced operational tasks and routine set-ups of machinery and is able to identify problems. Person is also able to perform routine quality inspections.

Level III

In addition to level II skills, the person is able to perform advanced set-ups and can diagnose problems, determine the root cause(s), and perform routine rework/corrective actions. Person is also able to record and track quality inspection data.

Level IV

In addition to level III skills, the person is able to recommend rework/corrective actions and can perform advanced level rework/corrective actions. Person is also able to work with QA to develop QA checklists for new products.

Levels of Expertise for Administrative Tasks

Level I

Person possesses a set of routine operational skills in order to perform any of the administrative tasks.

Level II

In addition to Level I skills, person is able to handle routine production paperwork and is able to identify manufacturing and/or quality problems. Person is also able to diagnose routine-level problems and can monitor work flow through the department and expedite backorders.

Level III

In addition to Level II skills, person is able to interface with production staff and support groups and can diagnose manufacturing and/or quality problems and develop corrective actions for routine-level problems. Person is able to perform short-term (one week) scheduling of associates and jobs on the floor. Person is also able to perform training of department associates.

Level IV

In addition to Level III skills, person is able to develop corrective actions for advanced-level manufacturing and/or quality problems. Person is able to perform associate evaluations and can determine appropriate staffing levels. Person is also able to work with planning to develop long-term (8 weeks) production schedules.

Assembly & Polish

Level I Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
basic polishing skills	A1,A4	16	320
operation of a drill press	A2,A5	1	4
operation of glass beading machine	A3	1	8
ability to glass bead parts to uniform color	A3	included above	included above
ability to unclog glass bead hoses	A3	included above	included above
ability to use "go-no go" gages	A1,A4,A7	0.25	0.5
ability to use vernier calipers	A1,A4,A7	0.25	0.5
ability to read and understand a blueprint	A1-A8	8	4
ability to read and write English	A1-A8	2-3 years?	
operation of Di-acro bending machine	A5	1	4
operation of comparator	A5	1	4
operation of riveting machine	A6	0.5	2
Analytic Skills			
knowledge of contact wheels and belts	A1,A4,A7	1	500
knowledge of belt life and replacement needs	A1,A4,A7	1	500
knowledge of drill bit wear and replacement needs	A2	1	500
knowledge of polishing wheels, compounds and wheel life	A4,A7	1	500
knowledge of how pin size & length affect the quality of the riveting operation	A6	1	200

Assembly & Polish

Level II Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level I skills plus:			
good hand-eye coordination for riveting small pins	A6	0	0
ability to shape contact wheel	A1,A4,A7	1	4
advanced polishing skills - polishing to tight tolerances with consistently uniform tapers and shapes	A7	40	1200
ability to inspect and determine "feel" of instrument	A8	2	160
ability to change worn wheels and belts	A9	1	0.5
ability to reshape wheels when out of balance	A9	1	4
ability to follow guidelines & established methods	Q1	prerequisite	0
must be a responsible, detail-oriented person	Q1	prerequisite	0
knowledge of product codes, lot numbering, & material traceability	Q3	2	0
ability to properly identify rejectable flaws	Q4	8	320
operation of hardness tester	Q5	2	2
operation of all measurement tools and devices	Q6	0.5	2
Analytic Skills			
all Level I skills plus:			
knowledge of speeds and feeds	A2	8	160
ability to identify problems	A1-A9	3	320
knowledge of intended use for instrument	Q4,Q5,Q6	3	0
Integrative Skills			
knowledge of standard test procedures, test methods, COP's	Q4,Q5,Q6	8	0
knowing when to get a second opinion before accepting or rejecting	Q4,Q5,Q6	2	320

Assembly & Polish

Level III Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level II skills plus:			
ability to perform routine rework or adjustments	A6,A7,A8	4	80
basic data entry and computer manipulation	Q7	8	20
Analytic Skills			
all Level II skills plus:			
ability to diagnose problems	A1-A9	24	320
ability to identify root cause(s)	A1-A9	included above	included above
knowledge of rework/adjustment techniques	A1-A9	4	0
knowledge of fixture wear and replacement needs	A2,A5	2	0

Assembly & Polish

Level IV Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level III skills plus:			
ability to perform advanced rework or adjustments	A1-A9	0	160
ability to sharpen drill bits	A2,A5		
ability to calibrate all measurement equipment	A1-A8,Q6		
knowledge of inspection techniques	Q2		
Analytic Skills			
all Level III skills plus:			
ability to recommend rework procedures or adjustments	A1-A8	0	160
knowledge of sampling rules	Q2	4	4
Integrative Skills			
all Level III skills plus:			
knowledge of department's manufacturing processes	Q2		
knowledge of similar products	Q2		

Parts Machining

Level I Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
operation of wire EDM machine including wire changeovers	M2,M3	20	90
ability to read and understand detailed blueprints	M2-M6	40	0
ability to read and write English	M2-M7	prerequisite	
operation of all measurement tools and devices	M2-M6,Q6	8	40
ability to operate CNC machine controls	M2-M5	40	120
ability to make tooling offsets	M4,M5	4	12
ability to correctly remove burrs when necessary	M6	2	16
Analytic Skills			
understanding of basic math formulas	M4,M5,M6	prerequisite	
knowledge of tool wear characteristics & replacement needs	M4,M5	3	8

Parts Machining

Level II Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level I skills plus:			
operation of heli-arc welding machine	M1	2	10
basic knowledge of tools	M5	4	2
ability to change and/or clean water and air filters	M7	2	4
ability to replenish way lube in all machines	M7	1	1
ability to change out water or coolant as needed	M7	2	4
ability to follow guidelines & established methods	Q1	prerequisite	
must be a responsible, detail-oriented person	Q1	prerequisite	
knowledge of product codes, lot numbering, and material traceability	Q3	6	2
ability to properly identify rejectable flaws	Q4	8	320
operation of hardness tester	Q5	2	2
Analytic Skills			
all Level I skills plus:			
knowledge of EDM operating parameters and how to adjust them during setups	M2	40	120
knowledge of speeds and feeds for milling	M5	24	50
knowledge of routine maintenance requirements	M7	10	8
ability to identify problems	M1-M7	3	480
knowledge of intended use for instrument	Q4,Q5,Q6	3	0
Integrative Skills			
knowledge of standard test procedures, test methods, COP's, etc.	Q4,Q5,Q6	8	0
knowing when to get a second opinion before accepting or rejecting	Q4,Q5,Q6	2	320

Parts Machining

Level III Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level II skills plus:			
basic data entry and computer manipulation	M6,Q7	8	20
ability to make routine adjustments until acceptable parts are achieved	M5	16	80
Analytic Skills			
all Level II skills plus:			
knowledge of fixture wear and replacement needs	M4,M5		
knowledge of CNC programming	M5	40	300
knowledge of surface finishes and how tool action affects the finish	M5		
basic knowledge of SPC	M6	40	20
ability to diagnose problems	M1-M7	24	320
ability to identify root cause(s)	M1-M7	included above	included above

Parts Machining

Level IV Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level III skills plus:			
ability to sharpen tools	M5	40	120
ability to calibrate all measurement equipment	M2-M6,Q6	16	40
ability to perform advanced rework or adjustments	M1-M7		
knowledge of inspection techniques	Q2		
Analytic Skills			
all Level III skills plus:			
ability to recommend rework procedures or adjustments	M1-M7	0	160
knowledge of sampling rules	Q2	4	4
Integrative Skills			
all Level III skills plus:			
knowledge of department's manufacturing processes	Q2		
knowledge of similar products	Q2		

Administration, Coordination & Planning

Level I Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
ability to read and write English	C1		
ability to read and understand detailed blueprints	C1	12	4
understanding of basic mathematics formulas	C1		
ability to operate standard computer software packages	C1	80	80
trust of fellow associates	C1		
Integrative Skills			
knowledge of accounting systems, Codman procedures, GMPs, operating procedures, etc.	C1	160	0
knowledge of job levels and required skills	C1	4	0
knowledge of compensation plan	C1	4	0

Administration, Coordination & Planning

Level II Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level I skills plus:			
ability to document corrective actions	C2,C3,C10	4	4
Analytic Skills			
all Level I skills plus:			
ability to identify bottleneck operations	C6	16	40
knowledge of intended use for instrument	C2,C3,C10	2	0
knowledge of potential rework actions	C2,C3	2	160
ability to identify problems	C2,C3	3	160
ability to determine which problems require corrective action	C3	0	160
Integrative Skills			
all Level I skills plus:			
understanding of functional tasks	C2,C3,C5,C7,C10,C13	16	0
understanding of skills required to perform tasks	C5-C7,C11	160	0
knowledge of backorders and job priorities	C4,C6,C11,C14	1	320
knowledge of work flow through department	C6	1	320
knowledge of OSHA & Codman safety regulations	C8	16	0
knowledge of who to contact for corrective action	C8	0	0

Administration, Coordination & Planning

Level III Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level II skills plus:			
ability to present and explain results of an investigation to a group	C12	24	8
ability to perform training sessions	C7	16	8
Analytic Skills			
all Level II skills plus:			
ability to identify root causes and develop solutions	C2,C3,C5,C10,C13	24	320
knowledge of associates' strengths and weaknesses	C4,C5,C7,C9,C11	0	1 year
understanding of training required to develop each skill	C7		
Integrative Skills			
all Level II skills plus:			
ability to consult with production staff and support groups to solve problems	C2,C3,C5,C10,C13		
understanding of business objectives	C4,C6,C14	8	0
ability to identify training needs within the department	C7		

Administration, Coordination & Planning

Level IV Skills	Tasks Requiring Each Skill	Training Time Required (hours)	Practice Time Required (hours)
Operational Skills			
all Level III skills plus:			
working knowledge of MAC-PAC system	C14	16	4
"people" skills	C1		
- ability to listen	C1		
- ability to ask the right questions	C1		
- ability to balance personal & professional needs	C1		
Analytic Skills			
all Level III skills plus:			
ability to develop advanced-level corrective actions	C2,C3,C5,C10,C13		
Integrative Skills			
all Level III skills plus:			
ability to balance and manage the work force schedule to meet business objectives	C4,C6,C14		
ability to identify associates' performance levels	C9		
ability to evaluate/distribute compensation fairly	C9		

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