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A METHOD FOR SETUP TIME REDUCTION IN HIGH PRECISION MACHINE CELLS

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(ABSTRACT)

This research focused on an important aspect of production, machine changeover or setup time. Setup time is defined as the elapsed time between producing the last part from the most recent lot to the first part of an incoming lot. The research had four objectives. First, an existing method to reduce machine changeover time was evaluated in a high precision machine cell (HPMC). Second, the causes and effects of setup problems in a HPMC were identified. Third, a method to reduce setup time was developed to more fully address some of the identified problems. Fourth, the developed method was evaluated in another HPMC.

After reviewing published setup reduction methodologies, the Single Minute Exchange of Dies (SMED) approach was selected for evaluation in machine cells. According to its developer, SMED can typically reduce setup time by 70 to 90%. The case study did not fully support this claim. Possible explanations for the mixed results were developed. Also, a number of setup problems were not fully corrected. These problems included machine and tooling failures, delays from tasks not completed at the machine area and labor related problems.

A method to reduce setup time was developed. The method applied the work simplification approach to reduce setup time. The developed setup reduction method consisted of five steps: (1) document the existing method, (2) simplify the current method while using the same tooling and procedures, (3) identify opportunities to reduce setup time, (4) prioritize the opportunities and (5) implement the prioritized projects. The method includes the basic setup reduction principles of SMED and addresses problems that were not fully corrected by SMED.

The developed method was tested in another high precision machine cell. An additional 22% reduction in setup time occurred as a result of correcting problems not fully addressed by SMED. It was concluded that because the new method focused on the manpower, materials and the methodology used during a changeover, it reduced setup time further than existing methods.

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Chapter 1

Introduction

1.1 Overview

Japanese manufacturers have recently made significant breakthroughs in improving quality, shortening production time and increasing productivity. As a result, Western companies have been steadily losing their ability to compete in both domestic and world markets. According to the National Research Council [1984], a major reason for the decline in the rate of growth of Western companies is the gradual emergence of a technology gap. To regain their market share, Western manufacturers are striving to produce high precision, customized goods in a timely manner and to reduce production costs.

A goal for Western manufacturers which strive to remain competitive is to shorten production time. Besides direct production operations, the total time to make a product includes time spent in storage, setup, transit, inspection, packaging and all other idle time. According to James Apple [1963], direct machining accounts for only 20% of the total production time. Therefore, in order to shorten production time, the time to complete both productive and nonproductive operations must be reduced.

One method to lower the overall production time is to organize machines into manufacturing cells. A manufacturing cell can be defined as a group of machines that are strategically arranged to produce similar part families [Groover and Zimmers, 1984]. Part families are products that are grouped together which share common dimensions or manufacturing requirements [Groover and Zimmers, 1984].

There are several benefits in organizing machines into cells. First, manufacturing cells promote efficient use of the machines, tooling and manpower. Second, within the cells, a reduction in the amount of materials handling or work flow may occur. Production lead time is lowered as the amount of material handling diminishes.

Another significant component of production lead time in a manufacturing cell is the machine changeover or setup process. Setup time can be defined as the elapsed time between producing the last part of one lot to the first good part of the next lot. The time needed to complete a setup can vary from machine to machine and from operation to operation. It is important to realize that if one setup is delayed or prolonged, all subsequent operations will be affected.

In the past, when lot sizes were large, the setup time per part was insignificant. Recently, the average lot size has been decreasing and the number of setups per year has been increasing (see Table 1). When the lot size is reduced, the setup time per part increases (see Table 2 on page 3.)

Table 1. Yearly Lot Sizes and Setups Per Year for a Bearing Manufacturer

Year	Lot Size	Setups/Year
1976	4900	1500
1980	4200	1950
1984	2700	1700
1988	1418	2261
1989	1311	2528

Table 2. Setup Time Per Part Versus Lot Size

Lot Size	120 Min. Setup	240 Min. Setup
10000	0.012	0.024
5000	0.024	0.048
1000	0.120	0.240
500	0.240	0.480
100	1.200	2.400
50	2.400	4.800

The data set in Table 1 indicates that the average lot size will continue to drop. Also, the demands for product customization and precision will increase. To meet these demands and remain competitive, companies must be able to flexibly produce high quality products in small lots. This will better enable them to rapidly respond to changes in the marketplace.

This research focuses on an important aspect of a flexible, small lot manufacturing cell; setup time. By minimizing setup time, a cell can be rapidly changed over to produce different products, thereby providing flexibility. Also, minimizing setup time helps to shorten the overall production cycle.

1.2 Statement of the Problem

Setup time is defined as the elapsed time between producing the last part of the most recent lot to the first good part of a new lot. This operation is not just replacing tooling, but also making adjustments, completing any paperwork and preparing the work area for production.

Each step in a machine setup can be classified as being an internal or external element. An internal element is a task that must be performed while the machine is stopped. An external element is one that can be completed while the machine is still running. An example of an internal element is changing a spindle motor. An example of an external element is getting new tooling for a setup.

Setup elements can also be classified by where they are performed. In general, there are two categories, on-site and off-site elements. On-site elements are those tasks that are completed at the machine area. Off-site elements are performed in areas away from the work center. Also, off-site elements can be completed by other individuals or service departments. For example, to verify that a machine is properly set, a special inspection test may be performed by somebody other than the setup operator. If a test is completed away from the machine, it is classified as an off-site element. Another off-site element is tool crib personnel preparing a kit for the next setup.

Mathematically, each machine changeover can be written as summation of setup elements.

$$T = \sum_{i=1}^{j} E_{ni}(1 \pm X_i)Y_i + \sum_{i=1}^{k} E_{fi}(1 \pm X_i)Y_i + \sum_{i=1}^{l} I_{ni}(1 \pm X_i)Y_i + \sum_{i=1}^{m} I_{fi}(1 \pm X_i)Y_i \qquad [1.1]$$

where:

T = Setup time

n = On-site element.

f = Off-site element.

E = Average acceptable time for an external element.

I = Average acceptable time for an internal element.

j = Total number of on-site external elements.

k = Total number of off-site external elements.

l = Total number of on-site internal elements.

m = Total number of off-site internal elements.

X = Percent variation from the average acceptable time.

Y = Frequency of performing an element.

For a particular setup, the values of each Y_i term is zero or one. If the element is not performed, Y_i is equal to zero. If the element is performed, Y_i equals one. For example, a special inspection test may be required if requested by a customer. For this element, Y_i equals one if the test is requested or zero if it can be omitted. The overall frequency of an element can be found by monitoring the individual Y_i terms over time.

All four types of setup elements (off-site internal, etc.) consist of three components: the average time of each element, the amount of variation from the average time and the frequency of each element. To reduce the total setup time, each component should be minimized. The time saved by minimizing a component varies from machine to machine and from operation to operation.

In general, machine operations can be classified as being low precision or high precision. A high precision operation is typically one that either removes a small amount of material, has tight tolerances, and/or has special allowances or constraints. An example of a high precision operation is finish grinding a circular raceway for a bearing that is to be used in a dentist drill. A low precision operation, such as rough cutting bar stock, is usually simpler to perform.

For high precision operations, it is especially important that a machine changeover is properly completed. Therefore, the setup time for a high precision operation may be longer than a low precision operation. There are two reasons for the difference in setup time for the two types of operations. First, high precision operations may have extra adjustment or inspection elements. Second, the time needed to complete some setup elements for a high precision operation may vary more than a low precision operation. To illustrate this point, consider how long it takes to thread a needle. If it is done on the first try, the setup time is short. If six attempts are made, the setup time becomes significant.

A distribution of setup times for a high precision bearing grinder was plotted (Figure 1 on page 6) to show the effects of setup time variation. The sample size of the distribution was 67 setups. The target setup time was 4.6 hours. This number was the mode of the distribution. The variability in completing a setup increased the average setup time to 6.7 hours. Also, excessive variation can increase the probability of having a long setup.

Different setup reduction methodologies exist. In general, there are two groups of reduction methods: frequency-based methods and process-based methods. Although, both types of methods lower the total machine changeover time their approaches differ. Frequency-based methods reduce

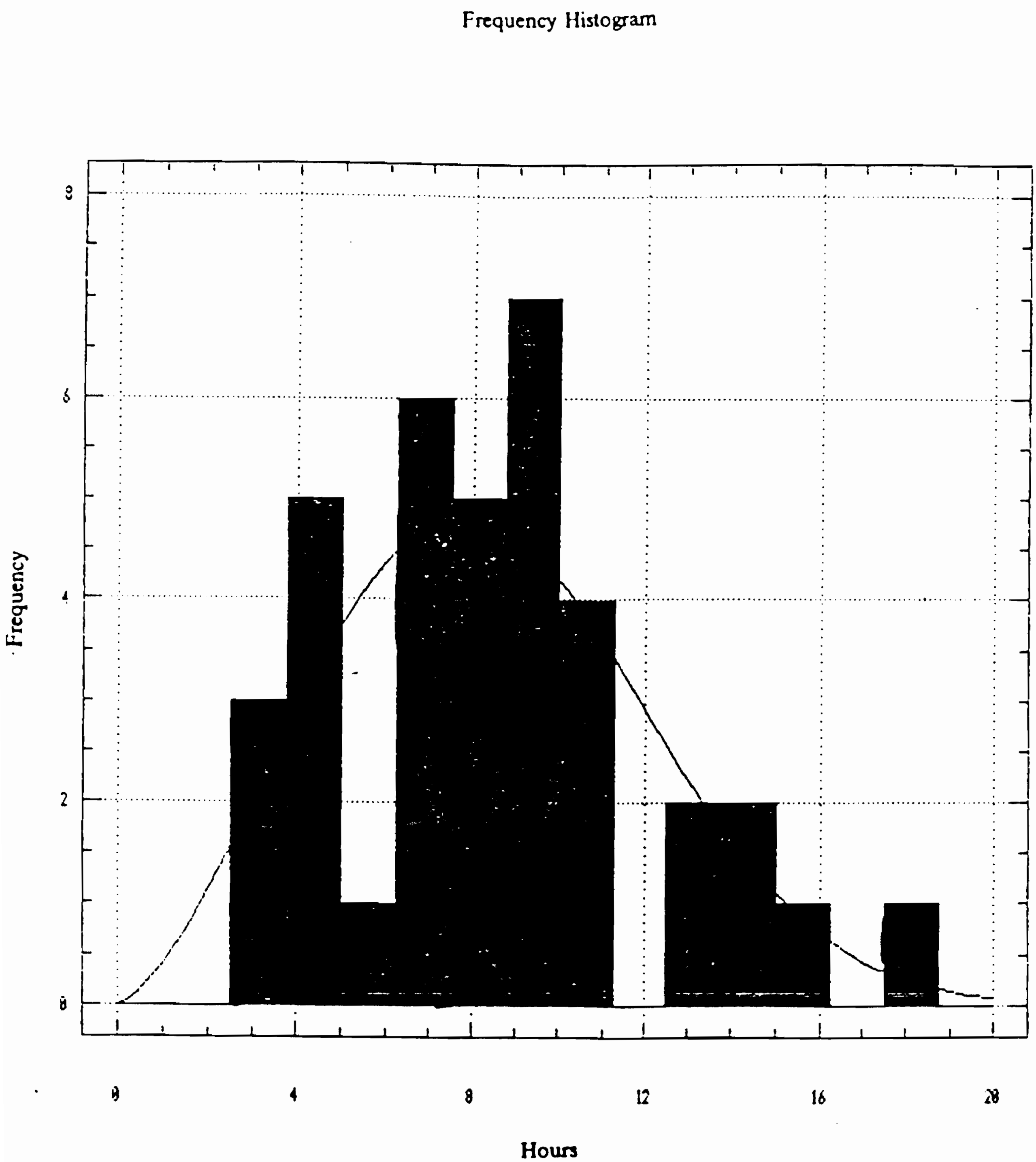


Figure 1. Distribution of Setup Time for a High Precision Operation

or eliminate the need to complete parts of the setup. Process-based methods simplify the changeover method.

Frequency-based methods reduce the number or occurrence of setup tasks by enhancing tooling, running larger lot sizes and/or using group technology. Enhanced tooling increases the number of functions and/or its tool life. If the tool life is extended, it may not have to be regularly changed. If the number of functions is increased, the amount of tooling that needs to be changed during a setup can be reduced.

When a manufacturing runs large lots, the number of setups per year is reduced. Although machining large lots may reduce the total setup hours per year, it is not consistent with current manufacturing objectives. Such objectives include reducing inventory size and costs, shortening production lead time and increasing manufacturing flexibility. Group technology, which is often used in machine cells, organizes parts into families. Part families can be defined as products which have similar characteristics or manufacturing operations [Groover and Zimmers, 1984]. As a result, members of a part family often require the same tooling. If similar parts are consecutively manufactured, the amount of tooling that needs to be changed is minimized.

In most high precision machine cells, a fixed number of operations and part sizes exists which limits the number of required tool functions. Most cells also incorporate the concepts of group technology. The amount of tooling that needs to be changed is minimized when a cell has a limited number of required tool functions and use group technology. Therefore, the basic structure of machines cells enables them to capture most of the benefits obtained from frequency-based methods.

Process-based reduction methods shorten and simplify the changeover process. Most guidelines (Dar-El [1986], Hays [1987], Robbins [1989], and Sepehri [1987]) include the basic principles of Shigeo Shingo's method, the Single Minute Exchange of Dies (SMED). The first principle of SMED is to reduce the machine changeover time by converting internal elements to external elements. The total machine down time is reduced when additional elements are completed while the machine is operating. The second principle of SMED is to simplify and shorten both internal and external elements.

Both frequency-based methods and process-based methods reduce machine changeover time. These methods present general guidelines. They do not, however, address specific problems encountered during a high precision operation setup, such as variation. This research seeks to identify these specific problems and to develop a standardized method for setup reduction in high precision machining cells.

1.3 Statement of Objectives

The purpose of this research was to identify specific problems associated with machine changeovers in a high precision machine cell (HPMC) and then to develop and validate a method for setup time reduction. The research had four objectives:

The first objective was to evaluate Shingo's method, the Single Minute Exchange of Dies (SMED), in a HPMC. There were two purposes of this objective. First, the stated reduction claims were tested. Second, the method's strengths and weaknesses were determined.

The second objective was to identify significant setup problems for both internal and external elements. A list of problem causes and effects was also developed. This information was later used to develop a method to reduce machine changeover time. One hypothesized problem given special attention in this research was setup time variation.

The third objective was to formulate an approach for setup time reduction in high precision machine cells. The method applied the work simplification approach to reduce setup time. The method incorporates the basic principles of SMED and addresses specific problems encountered in these areas. The method also includes a procedure for prioritizing opportunities to reduce setup time.

The fourth objective was to validate the new method by applying it to a case study. The strengths and weaknesses of the developed method were identified. Also, the effectiveness of the new method was determined.

1.4 System Definition

All research and experimentation were performed in high precision machine cells. According to Groover and Zimmers [1984], a machine cell is defined as a group of machines that are strategically arranged to produce similar part families. Part families are products which can be grouped together by similar dimensions, characteristics or manufacturing operations. The purpose of organizing machines into cells is to promote an efficient flow of parts and/or use of tooling. An efficient flow of parts can be obtained by positioning machines which perform consecutive manufacturing operations for a part next to each other. This can also be done by moving cells together which perform consecutive manufacturing process. As a result, the amount of material handling is reduced. Better control of tooling can be achieved by dedicating it to a cell. Also, because most cells are arranged to machine products for a particular part family, they often apply the concepts of group technology.

The types of manufacturing operations that are performed in a machine cell can vary. One way to classify operations is through the amount of required precision. An operation which requires a high amount of precision may have tight tolerances, removes small amounts of material or have special constraints. Low precision operations usually do not have such constraints. For example, rough cutting jobs are classified as low precision operations while finish cutting jobs are high precision operations. A high precision machine cell can be defined as a cell which performs one or more high precision operations. An example of a high precision cell is one which finish grinds a part, cuts a complex angle or improves the surface finish of a part.

In general, a manufacturing cell can follow one of three patterns: a single machine cell, a group machine layout or a flow line design [Groover and Zimmers, 1984]. The single machine cells are used for parts whose characteristics allow them to be manufactured using one process. An example of a single machine cell may be an advanced CNC machine. The group machine layout is a cell design which places machines together that manufacture a family of parts. An example of a group machine layout is a rough grinding machine and finish grinding machine that are placed next to each other. The third type of machine cell, flow line design, is similar to the group machine layout except that the machines are connected to each other by a conveyor or another automated material handling device. This type of cell promotes efficient work flow, but it may reduce manufacturing flexibility.

The research was performed in three different machining cells. The selected cells were arranged in a group machine layout. Also, the operations performed by these machines represent those that are completed in a high precision machine cell.

Chapter 2

Literature Review

2.0 Overview

Literature about reducing setup time and prioritization routines was reviewed. The findings are organized into four categories; process-based reduction methods, frequency-based reduction methods, miscellaneous reduction methods and prioritization routines.

Although the objective of all three reduction methods is to reduce setup time, their approaches vary. The goals of process-based methods are to complete setup tasks while the machine is still running and to simplify each step in the changeover process. The objective of frequency-based methods is to reduce or eliminate the need to change pieces of tooling or the machine settings. Although most techniques and guidelines fall into these two categories, exceptions exist. These types of reduction methods may only provide one particular approach or solution. Specific examples of process-based, frequency-based and other reduction methods are presented in Sections 2.1, 2.2 and 2.3, respectively.

While conducting a setup reduction project, a number of opportunities to reduce setup time are identified. However, because constraints may exist, such as available capital or manpower, every opportunity cannot be implemented. Therefore, some method must be used to evaluate these alternatives. It has been found that alternatives can be evaluated by economic and noneconomic methods. Specific examples of each method are presented in Section 2.4.

2.1 Process-Based Methods

Research has been conducted by several individuals to find techniques to simplify the changeover procedure. From their efforts, process-based methods were created. The goal of process-based methods is to reduce machine down time by performing some tasks while a machine is running and by shortening the time needed to complete each setup task. The main difference between process-based and frequency-based methods is process-based methods reduce the time needed to complete a task instead of determining how they can be eliminated.

One of the first formal methods for setup reduction was created by Shigeo Shingo [1985]. His method, the Single Minute Exchange of Dies (SMED), is presented in Section 2.1.1. Shingo stated that the average changeover time can be reduced by completing setup tasks while a machine is still running and by simplifying each step in the process. Because SMED is one of the first proven techniques for setup reduction, most process-based methods incorporate its basic principles.

Another method for setup reduction was created by Edward Hay [1987]. Hay's approach is a modification of SMED. There are two significant differences between Hay's approach and SMED. First, Hay requires a team of individuals to perform the analysis. Second, Hay states that the setup team should focus its attention in four areas; converting internal elements into external elements, and minimizing the time spent making adjustments, clamping and solving problems. Hay's method is further explained in Section 2.1.2.

Other authors have developed process-based reduction methods. These methods include the basic principles of SMED, but place an additional emphasis on other aspects of setup reduction, such as ergonomics or information flows. These methods are explained in detail in Section 2.1.3.

2.1.1 Single Minute Exchange of Dies - SMED

A pioneer in the field of setup reduction is Shigeo Shingo. Shingo's method for setup reduction is known as the Single Minute Exchange of Dies (SMED) [1985]. According to Shingo, setup operation can be reduced by 70 to 90 percent. Also, Shingo's method can be used for most manufacturing operations. Exceptions do exist. For example, some chemical operations may not be able to use all quick changeover techniques because the safety of workers may be at risk.

SMED consists of three phases (Table 3 on page 14). The first phase is to document the current setup method and analyze each step. Shingo states that there are two types of setup tasks, internal and external [Shingo, 1985]. An internal setup element is one that must be done while the machine is stopped. An example of an internal element would be changing a motor. An external element is a task that could be done while the machine is running, such as getting tooling.

During the first phase of SMED, each element is classified as being internal or external. Efforts are made to complete external elements while the machine is running. Often, before the setup reduction study occurs, a number of elements which could be done while a machine is running are completed while the machine is stopped. For example, tooling may be brought to the machine after the production stops. After completing phase 1, Shingo states that a 30 - 50 percent reduction in setup time can occur. Another author, Productivity Inc. [1988], claims that a 50 percent reduction can occur.

Table 3. SMED Method for Reducing Setup Time
Phase 1: Separate Internal and External Elements
Phase 2: Convert Internal Elements into External Elements •Duplicate tooling •Function standardization
Phase 3: Streamline Both Internal & External Elements •Eliminate unnecessary tasks •Use quick release clamps •Install calibrations or stops to simplify adjustments

The second phase of SMED is to convert internal elements into external elements. Two methods are presented. First, if duplicate tooling is available, additional setup tasks can be completed in advance or preset. The second method is to standardize the function of some equipment [Shingo, 1985]. Function standardization is modifying pieces of equipment so that they do not have to be regularly changed or adjusted. After completing Phase 2, Shingo and others (Productivity) claim that a 25 percent in the setup time can occur.

Phase 3 is to streamline both internal and external elements. This is accomplished by simplifying the installation and adjustment processes. Making adjustments can consume up to 50 percent of the setup time [Shingo, 1985]. Therefore, a significant amount of time can be saved by shortening the adjustment process.

There are two techniques for reducing adjustment time: (1) placing calibrations on the machine to eliminate guess-work and (2) using quick release clamps or single turn screws instead of fully threaded nuts and bolts. It has been shown by Shingo and others that the traditional nut and bolt is one of the most time consuming clamping methods. Also, it is one of the more common clamps in American companies.

As stated earlier, the purpose of phase 3 is to simplify both internal and external elements. Streamlining an internal element directly reduces machine down time. It is just as important to streamline external elements. Streamlining an external element does not directly lower the setup time. However, if an operator is not able to finish all required external elements before the setup begins, setup delays will occur until all tasks are completed.

After completing phase 3, Shingo and others (Productivity Inc.) claim that a 15 percent reduction from the total setup time can occur. Table 4 lists the percent reduction and cost of each phase. The first phases have the greatest reduction in setup time with the least cost. This should not imply that Phase 3 should be avoided. A number of benefits are obtained after completing Phase 3. The benefits can be quantifyable and unquantifyable. Some hidden benefits from the third phase of SMED are listed in Table 5 [Productivity, 1988].

Table 4. SMED Costs and Percent Reduction in Setup Time

Phase	% Red.	Cost
Separate Int. & Ext. Elements	30-50	Low
Convert Int. Elements to Ext.	25	Medium
Streamline Int. & Ext. Elements	15	High

Table 5. Benefits of Streamlining Setup Elements

•Reduced errors	•Product quality improves
•Safer operations	•Better tool management
•Worker motivation	•Eliminate special skills
•Greater flexibility	•Eliminate setup 'blind' spots

SMED is a structured method for reducing machine changeover time. The method is clear and flexible to use. One weakness of the method is that it does not fully address any specific problems that one may encounter, such as goods or services not being readily available.

2.1.2 Rath and Strong Method - Edward Hay

Edward Hay, a consultant from Rath and Strong Incorporated, modified the SMED method of setup reduction. There are two differences between Hay's setup reduction technique and SMED.

First, Hay's method uses a team of individuals to reduce machine setup time. The purpose of forming a setup team is to involve more than one individual in the setup reduction process. Members on a setup team should include engineers, machine repairmen, setup operators and even union officials. Less time may be needed to reduce setup time when a diverse committee is involved with the project.

The second difference between Hay's method for setup reduction (Table 6 [Hay, 1987]) and SMED is the analysis technique. Hay states that setup time can be reduced by concentrating on four factors; internal/external, adjustments, clamping and problems [Hay, 1987]. According to Hay, the setup teams should document a setup and perform a pareto analysis to determine which factors are most significant. Figure 2 on page 17 displays a typical pareto analysis for a setup.

Table 6. Hay's Method for Setup Reduction

1. Select equipment
2. Select setup teams
3. Videotape a setup
4. Document the tape
5. Perform a Pareto analysis
6. Distinguish internal/external elements
7. Simplify the setup process

Internal/external factors are the same as in the SMED system. Hay recommends converting internal tasks into external tasks to reduce setup time. Shortening the adjustment time is another factor in Hay's method. Hay states that using preset stops or calibrations should significantly reduce the adjustment time. The third factor is improving the clamping methods. Like SMED, Hay realizes that bolts, nuts and screws are inefficient clamps. He recommends that the setup team should determine how much force is required of each clamp and find a more efficient clamping method.

The final factor is eliminating any problems that can occur during a changeover. Unlike SMED, Hay claims that as much as 50 percent of the total setup time has to do with things not happening

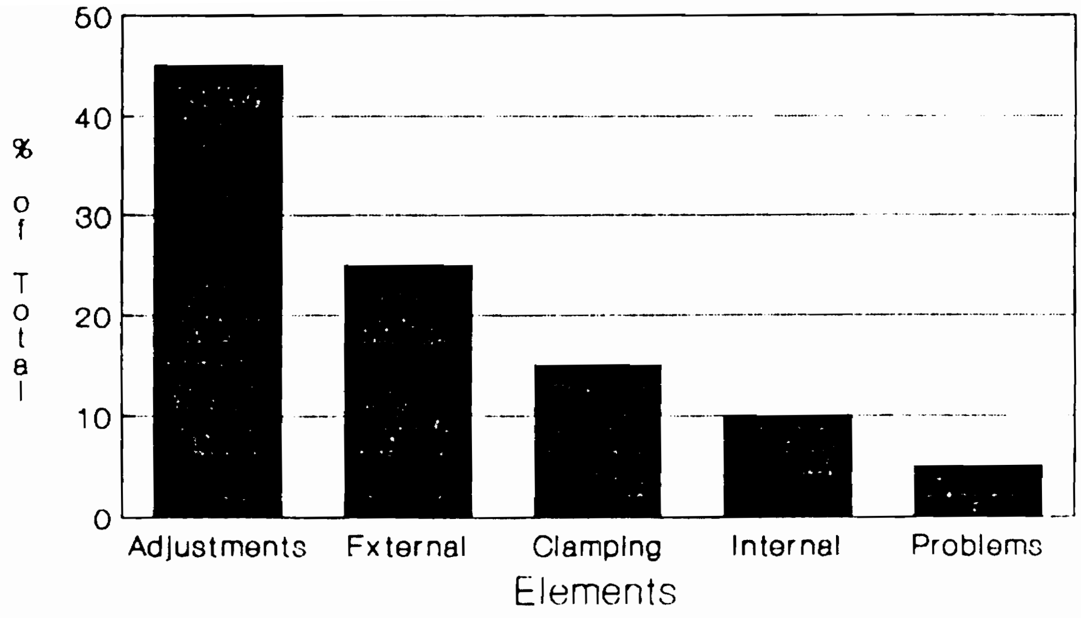


Figure 2. Pareto Analysis for Setup Time

or working the way that they were designed [Hay, 1987]. In order to reduce setup time, Hay states that the causes of such problems must be found and corrected. Hay does not provide a standard procedure on how to accomplish this task.

2.1.3 Process-Based Methods - Other Authors

Since Shigeo Shingo developed the SMED system, other authors (Dar-El [1986], Sepehri [1987] and Robbins [1989]) have created guidelines for setup reduction. The basic SMED principles are incorporated in these guidelines. Each author places additional emphasis on other aspects of setup reduction. Dar-El stresses the principles of motion economy and the need for training. Sepehri recommends modifying tooling to simplify adjustments and having procedure checklists. Robbins also recommends having checklists for both the tooling and the setup procedure. Each author's guidelines are further explained in the following sections.

A weakness of most guidelines is that although they present useful information, they do not give detailed instructions on how to perform the analysis or to correct specific problems. Also, these guidelines do not fully address each component of the setup process.

2.1.3.a Ezey Dar-El

One set of setup reduction guidelines was written by Ezey Dar-El [1986]. Dar-El's guidelines (Table 7 on page 19) are based on SMED. Also, Dar-El places additional emphasis on the principles of motion economy and training.

Table 7. Setup Guidelines - Dar-El
1). Minimize machine idle time by completing some activities while the machine is still running.
2). Shorten adjustment time by using presets and quick release clamps.
3). Apply basic ergonomics. Examples include having the work table set at a comfortable height and using rollers to move heavy equipment.
4). Lower the number of operations so that only one individual performs the setup. If more than one person completes a setup, their responsibilities should be clearly defined.
5). Provide training and practice for the operator who performs the setup.
6). Keep all tools, gages and other equipment clean and stored in the same location.

Dar-El realizes that good training and work methods are important factors to consider when reducing the setup time. Dar-El directly states that all employees should know what tasks are required of them. Dar-El's guidelines are not as detailed as SMED or Hay's. They state that improvements in reducing changeover time involve more than just simplifying the setup process. Also, Dar-El's guidelines are mainly for tasks performed at the work area only and do not consider off-site elements.

2.1.3.b Mehran Sepehri

Sepehri's six basic rules for setup reduction [1987] (Table 8 on page 20) are also based on SMED. Sepehri places additional emphasis on the design of future tools and the importance of having a written setup procedure. Like Dar El, Sepehri states that the setup reduction efforts should include the process, materials and and labor skills. Also, Sepehri's recommendations are for tasks performed only at the work area.

Table 8. Setup Guidelines - Sepehri

1). Convert internal elements into external elements.

2). Simplify fasteners and clamps.

3). Eliminate machine based adjustments.

4). Use block gauges and templates for adjustments.

5). Design tooling that can be used for multiple parts. Also, schedule parts which use the same tooling.

6). Eliminate unnecessary tasks. Setup procedures and setup teams help reduce these problems.

2.1.3.c Richard Robbins

Richard M. Robbins from Cleveland Consulting Associates recommends applying SMED with other quick changeover (QCO) activities [1989]. Robbins places additional emphasis on having tooling and procedure checklists available and performing functional tests. As shown in Table 9, QCO methods can be grouped into three categories: process, materials and manpower.

Table 9. Setup Guidelines - Robbins

Process:	
	•Use SMED system by Shingo.
Materials:	
	•Provide tooling checklists. •Label tools for quick identification. •Store tooling near the work area. •Perform functional checks on the machine and tooling before the setup begins. •Dedicate tooling to each machine.
Manpower:	
	•Provide procedure checklists. •Encourage team problem solving.

2.2 Frequency-Based Methods

In the past, Western manufacturers gave setup reduction studies a low priority. There were two reasons why setup studies were not considered. First, with large lot sizes, the machine changeover time per part was insignificant. Second, manufacturers and engineers thought that the variation in machine setup time would be difficult to control due to the large number of setup inputs. These inputs include each piece of tooling, outside services, incoming work, labor skills, etc. Also, each input could contribute to the overall variation in setup time. For these two reasons, setup reduction studies would occur only if the changeover time was excessively long. When a study would begin, it was believed that the best way to solve the problem was to reduce the need to perform the setup or individual tasks. It is for this reason that these type of setup reduction methods are titled frequency-based.

There are three approaches for reducing the need to perform portions of a machine changeover, system improvements, group technology and increasing lot sizes. System improvements are the modification of tooling, machinery or production control methods so that various setup steps do not have to be regularly performed. The works of two authors, Close and Niebel, are described in Section 2.2.1. Group technology organizes parts into product families. It has been stated that if similar parts are consecutively manufactured, the number of setup tasks can be minimized. The concepts of group technology and scheduling are defined in Section 2.2.2. A third approach to minimize the number of completed setup tasks is to increase the lot size. By machining large lot sizes, the number of setup per year can be reduced. The assumptions and formulas used for this approach are described in Section 2.2.3.

2.2.1 System Improvements

One solution for reducing machine changeover time is to improve the part clamping methods so that they do not need to be reset or replaced. One such set of guidelines was written by Guy Close [1960]. Close recommends that fixtures and clamps in a machine are easy to use and adjust. He also suggests that setup operators have references, such as models, drawings or templates of completed machine changeovers, to help guide them. Most of Close's ideas are for flexible part holding devices used during production. Such clamps may not need to be regularly changed or adjusted. Close does not provide any guidelines to simplify any other setup tasks.

Manufacturers have developed other alternative methods to reduce machine changeover time. One set of guidelines was written by Benjamin Niebel [1983]. Niebel states that better setup methods can be accomplished by (1) designing tooling to utilize full capacity of the machine, (2) improving the efficiency of the tooling, and (3) reducing setup time by better planning and production control.

Niebel recommends tooling be designed to utilize the full capacity of the machine. If tooling is constructed so that it can perform additional machining operations, it would not need to be frequently changed. As a result, fewer setups are needed. A second recommendation is to make the tooling more durable. Fewer changes would be needed for corrective and preventive maintenance if the tool life is increased.

A third recommendation is to improve the control of production. Niebel presents three methods to make such improvements. First, he advises having a dispatcher deliver and remove all tooling, gages and work. Second, duplicate tools should be kept near the machine to minimize down time waiting for repairs. Finally, a backlog of work should be kept so that machine idle time never occurs. In today's context, however, a backlog of parts is inefficient when using a just-in-time manufacturing system.

Niebel's recommendations correct problems associated with the setup materials and production control. The recommendations do not improve or simplify the changeover process.

2.2.2 Group Technology and Scheduling

Several authors recommend group technology to improve production control. As stated earlier, better production control can reduce changeover time. Group technology classifies products into part families. There are two general classification methods, obvious and nonobvious [Corke, 1977]. Some families are termed obvious because they all share a common characteristic. An example of an obvious family is parts with or without a shaft. Part families termed nonobvious also have similar components. However, they require some analysis before they are identified. Nonobvious families can be based on their manufacturing operations or by their shape, size or material.

Table 10. Advantages and Disadvantages of Group Technology

Advantages

- Shorter manufacturing lead times
- Reduced total setup time
- More efficient supervision of quality
- Greater job satisfaction
- Simplified production control procedure
- Reduced process planning costs
- Reduced manufacturing costs
- Reduced tooling costs

Disadvantages

- Possible low machine utilization
- Effort required to change an existing method to group technology

Table 10 lists some of the advantages and disadvantages of using group technology [Corke, 1977]. One advantage of group technology is the potential for reducing machine setup time. If parts that belong to the same family are consecutively manufactured, the amount of tooling that needs to be changed and adjusted can be minimized. As a result, the frequency of having to perform a complete, or major, setup is lowered. The advantage of having more partial or minor setups is based on two assumptions. First, it is assumed that similar parts are available to be machined. Second, it is assumed that completing portions of a minor setup does not require moving or adjusting other "fixed" parts of the machine.

Table 11 [Corke, 1977] lists an approach to introduce a group technology system. The first step is to define product families. The second step is to calculate the annual machine load for the part families. This information is used to determine if the current machine capacity is acceptable. The third step is to select the actual machines. It is assumed that there is excess machine capacity and available machines.

The fourth step to introduce group technology is to analyze the tooling. The purpose of this step is to determine the tooling requirements for the new system. The results of the analysis show which parts may complicate the system and how much additional tooling is needed. The results may also indicate where other improvements, such as increasing the functions of a tool, should be considered. The fifth step to introduce group technology is to simulate the operation in order to determine what problems and benefits should occur. Finally, the new system is installed.

Table 11. Procedure to Introduce Group Technology

1. Define product families.
2. Compute the annual load of the families.
3. Select the machines.
4. Analyze the tooling.
5. Simulate the operation.
6. Install the new system.

Group technology reduces setup time if similar parts are consecutively manufactured. There has been some discussion exists about the effect of scheduling parts by minimum setup costs and by other methods. S. L. Siegel [1987] developed a simulation program that compares different scheduling rules. The rules were: (1) scheduling by the earliest due date, (2) scheduling an order with the minimum setup cost, (3) scheduling an order that has the least dynamic slack per operation, (4) scheduling the order which requires the least manufacturing time and (5) scheduling the order that has the smallest amount of work on the next operation. Siegel tested each scheduling method by itself and in combinations. He concluded that the optimal scheduling rule depends on the type of product a company produces. Siegel did state that for products with high setup costs, scheduling production by the lowest setup cost as a main rule and earliest delivery date as a secondary rule yields the highest net profits.

2.2.3 Lot Sizing

Another method to reduce the setup time per part is to increase the lot size. This can be accomplished by delaying the production of some parts until a larger lot size is obtained. Running large lots reduces the number of setups per year. This approach to reduce setup time is based on the following formulas [Buffa and Taubert, 1972]:

$$Q_o = \sqrt{\frac{2c_P R}{c_H(1 - \frac{r}{p})}} \qquad [2.1]$$

$$TIC_o = \sqrt{2c_P c_H R(1 - \frac{r}{p})} \qquad [2.2]$$

where:

Q_o = Optimal lot size

TIC_o = Total incremental cost of an optimal solution

c_P = Preparation cost per order (includes setup costs)

c_H = Inventory holding cost per unit per year

R = Annual requirements in units

r = Daily usage rate

p = Daily production rate

Formulas 2.1 and 2.2 identify an optimal value for the lot size. As the setup cost would increase, the total preparation cost increases. Also, the optimal lot size would rise since the preparation cost is in the numerator of the equation.

This approach for reducing setup time is not useful in today's economic manufacturing environment for several reasons. First, companies are trying to reduce inventory costs. If parts are held to increase a lot size, holding costs will increase. Also, running larger lots promotes a build up of inventory as other lots wait to be manufactured. Second, the formulas assume that the setup costs, holding costs, production costs and other variables are constant. These assumption have been proven incorrect. It has already been stated by Niebel [1982], Shingo [1985], Hays [1987], and others that setup time and costs can be reduced. Finally, increasing the lot size only temporarily hides production problems, such as long setup times. These problems may get worse over time and eventually must be addressed.

Increasing lot sizes is also impractical for noneconomic reasons. First, recent trends indicate that lot and order sizes are decreasing. Table 1 on page 2 illustrates the reduction of lot sizes in the bearing industry over the past thirteen years. Second, manufacturers are attempting to increase flexibility in production scheduling and the number of machining operations. The total production time for large lots is greater than small lots. When large lots become common in a factory, some manufacturing flexibility is lots as fewer lots and operations can be scheduled over a time frame. As a result, manufacturers cannot readily respond to changes in the market demand.

2.3 Other Setup Time Reduction Methods

Additional articles have been written about reducing setup time that cannot be classified as a process-based or frequency-based reduction method. These articles address specific problems or solution methods which may not be applicable for all situations. Two such methods to reduce changeover time are better labor utilization and advanced automation.

2.3.1 Labor Utilization

Another method to reduce machine down time is to improve the use of labor resources. This can be accomplished by adding people to the setup, continuing setups through breaks and shift changes, and allowing overtime. The main purpose of the strategy is to minimize machine idle time.

Although the strategy can reduce machine down time, there are some constraints which prevent it from being widely used. First, union regulations exist. These regulations may require an employee to have a fixed lunch and break schedule. They also may prohibit a worker from being cross trained.

A second constraint which may prevent management from adding people to a setup is an increase of direct labor costs. Cost accountants may state that if a setup is reduced from six to four hours by adding a second person, production costs have risen as the total direct labor hours have gone from six to eight hours. The increase in direct labor costs should not always prevent the strategy from being implemented. Some benefits that cost accountants may fail to consider are a reduction in machine down time, an increase in machine capacity and a reduction in production lead time.

The availability of additional setup operators may also prevent the strategy from being used. Training individuals how to changeover a machine can be costly. Again, the question on whether a company's strategy should be reducing labor costs or lowering down time and increasing capacity arises.

Better utilizing labor resources can reduce machine down time. This can be accomplished by adding people to a setup, continuing setups through breaks or allowing overtime. Although constraints exists, they can be overcome if the purpose and objectives of this strategy are understood by both employees and management.

2.3.2 Automation

Another method for setup reduction is advanced automation. William Ehner and Franz Baz [1983] state in their article, 'Factory of the Future', that future manufacturing cells and machines should have the capability of partially automated or instantaneous setup changes. This strategy is unlike others because a company's only responsibility is to purchase and maintain this type of equipment. It is now the responsibility of machine manufactures to design tooling and machinery for immediate setup changes.

2.4 Prioritization Techniques

While conducting a setup reduction project, a number of opportunities to reduce setup time are identified. Although it initially appears that each idea should be implemented, constraints, such as available manpower or capital, exist. These constraints may limit the number of projects that can be implemented. Therefore, some method must be used to determine which opportunities will yield the most benefits.

There are a number of evaluation methods. These methods can be grouped into two categories, economic and noneconomic. Economic methods evaluate alternatives in terms of dollars. Noneconomic methods evaluate alternatives according to one or more criteria, such as time, safety or quality. Both types of evaluation methods are further defined in Sections 2.4.1 and 2.4.2, respectively.

2.4.1 Economic Evaluation Methods

In profit based organizations, the main objective of most projects is to make money. The objective for non-profit organizations is to maximize the benefits of a project. For either organization, when selecting an alternative, it is usually desired to chose the one which is most profitable or has the least cost.

A number of economic evaluation methods exist. The accuracy, complexity and thoroughness of each method varies. Some criteria which differentiate one method from another are inflation, tax considerations, replacement assumptions, time spans, and the time value of money or interest. A project, whose cash flow considers the effects of interest, is termed discounted while a cash flow that does not consider interest is termed undiscounted [Fabrycky, Riggs, Thuesen, West].

Two types of undiscounted evaluation methods are elimination by initial cost and the payback period. Projects can be initially eliminated by their first cost. This method is useful when there is little working capital. However, exclusive use of this method will yield suboptimal results because future costs and benefits are not considered. The payback period of a project is equal to the first cost of a project divided by its annual savings. The resulting number is the amount of time needed before the cost of a project is recovered through its benefits. Alternatives with quick payback periods are preferred. The payback period is one of the more popular criteria used in the United States [Riggs and West, 1986]. The weaknesses of the method are its assumptions that the annual savings will not change, there is no final salvage value for the project and the time value of money does not change.

Discounted evaluation methods assume that the value of money changes over a period of time. A discount factor is used to convert future expenses or incomes into current dollar values. This conversion factor can include current or anticipated interest rates, borrowing costs, expected inflation rates, risk factors and other criteria.

There are a number of economic evaluation methods that use discounted cash flows. Examples of such methods include the present worth, annual equivalent, future worth and incremental rate of return techniques. Although the assumptions and calculations of each method vary, comparisons between alternatives can be made.

Economic evaluation methods must convert an alternative's costs and benefits into dollars before making any comparisons. Some benefits, such as reduction in setup time, can be quantified. Others, such as safety, cannot. Therefore, economic evaluation methods may not fairly evaluate alternatives which have a number of significant, yet unquantifyable, benefits.

2.4.2 Noneconomic Evaluation Methods

Dollars may not always be the best measure to evaluate different alternatives. For these types of decisions, noneconomic measures or attributes are used. Examples of such measures are time, safety and quality.

According to a number of authors, there are two different types of attributes, objective and subjective. Objective measures can be quantified. Usually, objective measures are defined in terms of dollars. Subjective measures cannot be easily quantified. Although subjective measures may not be commonly used, they can be significant criteria. If these measures are not used to evaluate alternatives, incorrect decisions may be made.

Alternatives can be evaluated by a single attribute or by multiple attributes. When using a single attribute, alternatives are selected by either direct evaluation or by a Pareto analysis. Direct evaluation measures an alternative with respect to an attribute scale. The alternative with the largest or smallest value is selected. Pareto analysis can be used to select one or more alternatives.

Pareto analysis is the technique of arranging data according to priority [Amsden, 1967]. The analysis uses a cumulative distribution to determine which alternative account for the greatest proportion of problems. Therefore, pareto analysis is based more on an alternative's order of measurement rather than the value of the measurement. There are four steps in the analysis: (1) list all of the alternatives, (2) measure each alternative, using the same measurement scale, (3) order the alternatives according to their measure, and (4) create a cumulative distribution [Amsden, 1967].

Both Pareto analysis and direct measurement methods evaluate alternatives with respect to one criteria. However, these methods should not be used when there is more than one significant attribute. Instead, multiple criteria evaluation methods should be used.

Multiple criteria evaluation methods eliminate or prioritize alternatives so that a decision can be made. Elimination methods were first categorized by K. MacCrimmon in 1967 [Canada and Sullivan, 1989]. Alternatives can be eliminated by making comparisons to attributes or to other alternatives.

Eliminating alternatives by attribute comparisons is made through disjunctive or conjunctive constraints. When using disjunctive constraints, an alternative is eliminated if it fails to meet all standards. If one standard is meet, the alternative is retained. When using conjunctive constraints, an alternative is eliminated if it fails to meet any attribute standard.

MacCrimmon defines three methods to eliminate alternatives by cross comparisons: (1) dominance checks, (2) elimination by aspects and (3) lexicographic. If one alternative is better than (dominant) or equal to another alternative with respect to every attribute, the weaker alternative is eliminated. Elimination by aspects examines one attribute at a time. If an alternative cannot meet an attribute's minimum standard, it is eliminated. This process is continued until all attributes are reviewed or until all alternatives are eliminated. The lexicographic method ranks attributes by importance. The alternative which measures highest with respect to the attribute is selected. If a tie exists, the process is repeated using the second most important attribute. The remaining alternatives are then eliminated.

Canada and Sullivan [1989] present three methods to calculate attribute weights. First, equal weights can be assigned to each attribute. Second, rank sum weights can be calculated. Rank sum weights are found by first ordering the attributes. A weight is then calculated by using formula:

$$W_i = \frac{N - R_i + 1}{\sum_{i=1}^{N}(N - R_i + 1)} x100 \qquad [2.3]$$

where:

N = number of attributes

R_i = Rank of the attribute i

W_i = Weight of attribute i

The authors' third method to calculate weights is the rank reciprocal approach. Weights are calculated by using formula [2.4]. The formulas uses the same notation as the rank sum method.

$$W_i = \frac{\frac{1}{R_i}}{\sum_{i=1}^{N}\frac{1}{R_i}} \qquad [2.4]$$

Canada and Sullivan present a variation of the Brown-Gibson model to evaluate alternatives [1989]. The method determines a combined measure for each alternative that considers both objective and subjective measures. In formula form, the combined measure is

$$W_k = (\alpha)(OM_k) + (1 - \alpha)(SM_k) \qquad [2.5]$$

where OM_k = objective measure for alternative k

SM_k = subjective measure for alternative k

α = relative importance weighting for OM_k

Both OM_k, SM_k, and $0 \leq \alpha \leq 1$

There are two formulas for calculating the objective measure, OM_k. If the measure is profits, OFP_k, then

$$OM_k = \frac{OFP_k}{\sum_{k=1}^{K} OFP_k} \qquad [2.6]$$

If the measure is costs, OFC_k, then

$$OM_k = \frac{1}{OFC_k(S)} \qquad [2.7]$$

where

$$S = \sum_{k=1}^{K} \frac{1}{OFC_k} \qquad [2.8]$$

The formula for calculating the subjective measure, SM_k is

$$SM_k = \sum_{k=1}^{K} (\text{subjective attribute weight}) \times (\text{subjective evaluation rating}) \qquad [2.9]$$

Both the subjective attribute weight and evaluation rating are normalized. Normalized weights or ratings have been divided by the corresponding sum of weights or ratings. By normalizing both items, SM_k will be less than 1, (a prerequisite in using the modified version of the Brown-Gibson model).

After calculating the objective and subjective measure for each alternative, a combined score is found. The alternative with the highest score should be selected.

The strength of the modified Brown-Gibson model is its incorporation of priority weights for both subjective and objective measures. One weakness of the modified model is its assumption that only one objective measure, profits or cost, is used. If more than one objective measure is needed, the model will need to be modified.

Another method to evaluate alternatives was developed by Thomas Saaty [1980]. Saaty's method, the Analytic Hierarchy Process (AHP), decomposes a problem or objective into a number of attributes and/or subattributes. Pairwise comparisons are made about the preference of an attribute over the others. The scale presented in Table 12 defines a preference scale proposed by Saaty. After comparing each attribute, a preference matrix is written. Preference weights are found by calculating the principle vector or eigenvector of the matrix (Figure 3 on page 35).

Table 12. AHP Preference Scale - Saaty

If x is .... than y,	Preference Number
equally important/preferred	1
weakly more important/preferred	3
strongly more important/preferred	5
very strongly more important/preferred	7
absolutely more important/preferred	9

Each alternative is compared to each other with respect to each criteria. The same preference scale is used. A preference matrix is then prepared for each criteria. Also, an eigenvector is calculated. After finding an eigenvector for each criteria, a total score for each alternative is found. The alternative with the highest score should be selected. An example of calculating an alternative's score is shown in Figure 4 on page 36.

The advantages of AHP are its flexibility and thoroughness. Both subjective and objective measures can be incorporated. The method can also be used for a number of alternatives. Also, it can be modified to reflect any changes in the priority weights or significant attributes. A drawback of the method is the number of calculations. If too many attributes or alternatives are selected, the method may be cumbersome to use. As a result, the accuracy of the method may be reduced.

Selecting An Airline

Preference Matrix

	Attribute		
	A	B	C
A	1	1/2	2
B	2	1	5
C	1/2	1/5	1

Description

A = Schedule
B = Cost
C = Comfort

	A	B	C
A	1	1/2	2
B	2	1	5
C	1/2	1/5	1
Total	3.5	1.7	8

Step 1: Calculate the sum of each column.

	A	B	C
A	0.286	0.294	0.250
B	0.571	0.588	0.625
C	0.143	0.118	0.125
Total	1.000	1.000	1.000

Step 2: Normalize each column so that its sum is equal to 1.0. (Divide each number by its column sum.

	A	B	C	Vector
A	0.286	0.294	0.250	0.830
B	0.571	0.588	0.625	1.784
C	0.143	0.118	0.125	0.386
Total	1.000	1.000	1.000	3.000

Step 3: Calculate the matrix eigenvector. (Add the values of each row.)

A = 0.2767
B = 0.5947
C = 0.1287

Step 4: Normalize the vector to get the attribute weights. (Divide each number by the vector sum.)

Figure 3. AHP - Calculating Attribute Preference Weights

Selecting An Airline

Step 1: Evaluate each alternative, X Y & Z, with respect to each attribute

A. Schedule

	X	Y	Z
X	1	2	1/2
Y	1/2	1	1/4
Z	2	4	1

B: Cost

	X	Y	Z
X	1	2	1
Y	1/2	1	1/2
Z	1	2	1

C: Comfort

	X	Y	Z
X	1	1/4	1/4
Y	4	1	1
Z	4	1	1

Step 2: Calculate the normalized eigenvector for each matrix. (Use the method for calculating preference weights.)

	A	B	C
X	0.286	0.400	0.111
Y	0.143	0.200	0.444
Z	0.571	0.400	0.444

Step 3: Multiply each number in a column by its corresponding attribute weight.

	A	B	C
Weight	.277	.595	.129
X	0.079	0.238	0.014
Y	0.040	0.119	0.057
Z	0.158	0.238	0.057

Step 4: Calculate the score for each alternative by summing each row.

X = 0.2767
Y = 0.5947
Z = 0.1287

Figure 4. AHP - Calculating Alternative Scores

Chapter 3

Approach to Problem

3.0 Overview

The purpose of this research was to review existing setup reduction methods and to develop and validate a method for reducing setup time in high precision machine cells. The method was to address specific problems encountered in machine cells that existing methods overlooked.

There were four research objectives. First, the Single Minute Exchange of Dies method for setup reduction was evaluated in a high precision machine cell. Second, the causes and effects of significant setup problems were identified. Special emphasis was placed on a hypothesized problem, setup time variation. Third, a methodology was created for reducing machine changeover time in high precision machine cells. Fourth, the methodology was evaluated in another high precision cell. Each objective is further explained in the following sections.

The research was performed and validated in high precision machining cells at a bearing manufacturing facility. The observed operations were representative of those found in a high precision machine cell. Information concerning a case study is found in Section 3.5.

3.1 Evaluation of an Existing Setup Reduction Method

As mentioned previously, a number of setup reduction methods exist. These methods can be classified into two groups, process-based methods and frequency-based methods. The goal of process-based methods is to shorten and simplify all tasks throughout a changeover. The goal of frequency-based methods is to reduce or eliminate the need to complete portions of the setup. This can be accomplished by increasing the lot size so that fewer setups are performed per year, applying concepts of group technology, increasing tool life, or increasing the number of tooling or machine functions.

The research was completed in high precision machine cells. In a cell, a fixed range of parts and number of machining operations are assigned. Also, because the range of parts is limited, most machine cells utilize group technology. Therefore, if a frequency-based method was used to shorten setup time in a cell, the benefits would not be significant. It was assumed that cellular manufacturing already achieved the benefits of a frequency-based setup reduction method.

A process-based method was evaluated in two machine cells. Shigeo Shingo's method, the Single Minute Exchange of Dies (SMED), was used to represent a standard process-based method. SMED was selected for the following reasons. First, the fundamental principles of SMED are incorporated in most process-based methods. Second, the method has already been proven to be applicable to a variety of machining operations. Third, unlike other methods, SMED provides a specific set of instructions rather than a list of guidelines.

SMED was evaluated on representative machine cell operations. There were four issues that were addressed. First, it was to be determined if there are particular problems, such as time variation, that SMED does not fully consider. Second, it was to be determined if there were portions of SMED that did apply to high precision machine areas. Third, the actual results of SMED were to be compared to the method's expected reduction claims. Finally, setup problems unique to the selected high precision machining operations were identified and separated from the study. The data set gathered from the tests was later used to develop a method for setup reduction for high precision machine cells.

3.2 Identification of the Causes and Effects of Setup Time Variation

One problem that is frequently encountered in both high and low precision operations is variation in setup time. Variation can be defined as the extent to which the changeover process requires more or less time to complete than an accepted standard. If the amount of variation and the number of occurrences of longer-than-normal setup times is significant, the average changeover time and probability of having a long machine setup increases.

There are a number of causes for the amount of variation in setup time. For example, there may be different amounts of variation in the time needed to remove, install or adjust tooling. Therefore, this research objective was to identify significant causes and the effects of variation in setup time.

There were three subobjectives in identifying the causes and effects of variation. First, an acceptable level of variation was to be defined. Second, it was to be determined if only internal, external or both types of elements should be considered. Finally, it was to be shown if the causes of setup time variation were unique to high precision machine cells, to the selected operations, or to a particular machine.

To determine the causes and effects of setup time variation, three sources of information were reviewed: historical data, direct observation and interviews. Figure 5 on page 41 outlines how the research to determine the causes of variation was conducted.

The company sponsoring this research had a computerized labor reporting system. One function of this system is to document and summarize the time spent completing a setup, waiting for service, and other machine down time. These reports were used to determine general categories for the causes of variation. A set of data about the frequency and length of each type of delay was collected.

Machine changeovers were directly observed and documented. There were two purposes in directly observing machine setups. First, it provided an opportunity to observe and record problems which may not be documented using the company's labor reporting systems. Second, the validity of historical data was tested.

After observing machine setups for both bearing inner ring bore and outer ring race grinding cells, a survey was sent to each setup operator. The survey requested that each individual identify common causes of variation and the average delay length. The purpose of the survey was to provide additional insight to the causes and effects of variation.

After analyzing the surveys, a list of setup delay causes, frequencies and lengths was prepared. Also, it was shown whether or not each delay element is unique to the cell, operation or machine. Upon completing this portion of the research, specific machine changeover problems in high precision machine cells were identified.

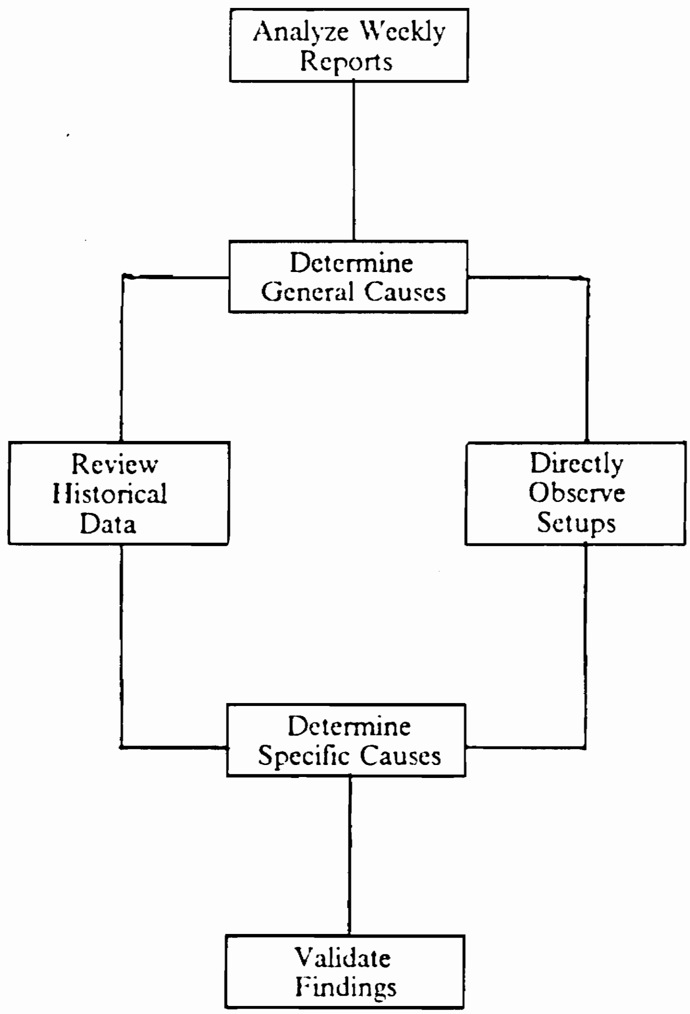


Figure 5. Indentification of the Cause & Effects of Variation in Setup Time

3.3 Development of the Method to Reduce Setup Time

A methodology for reducing setup time in high precision machine cells was developed. The purpose of the methodology was to reduce the average changeover time further than existing methods. Unlike generalized methods, the new method would address specific problems encountered in these areas.

The developed method applied the work simplification approach to reducing machine setup time. The methodology consisted of a detailed list of instructions similar to the SMED. However, some modifications were made to address problems in high precision machine cells. The methodology included additional instructions on how to identify and correct significant problems that other methods overlooked.

The developed method not only identified significant opportunities to reduce setup time but also prioritized them. The prioritization method considered criteria such as the delay time, the frequency of the element, the approximate correction time, the approximate correction cost and other subjective measures. These subjective measures included special concerns such as promoting safety and improving quality.

Multiattribute decision methods were reviewed. Existing methods were modified to create a method that prioritized opportunities to reduce setup time. One step in the prioritization method is to define a weighting scale. The purpose of the scale is to reflect the importance of one criteria over another. Once a weighting scale is found, opportunities are to be evaluated. A prioritized list of these projects is then prepared.

3.4 Evaluation of the Methodology

The developed methodology was evaluated in another high precision machine cell. The purpose of this cell was to hone the raceway of a bearing. Specific information about these machines can be found in Section 3.5.4.

The honing cell consists of five machines. Initially, the average setup time in the area was 5.1 hours. The standard deviation in setup time was 1.9 hours. The methodology was used to reduce the machine changeover time.

Three issues were addressed during the evaluation process. First, the effectiveness of the developed method was determined. Second, the additional reduction in setup time was compared to an existing method. Finally, the benefits or drawbacks of the method were identified.

3.5 Case Study

The Barden Corporation in Danbury, Connecticut, sponsored this research. The company agreed to allow an investigation into the setup methods and materials for various high precision machining cells. The operations which were selected as representatives of high precision machine cells are inner ring bore grinding, outer ring raceway grinding and raceway honing.

The Barden Corporation is a world leader in manufacturing high precision ball bearings. The company headquarters is in Danbury, Connecticut. The company consists of three divisions. The Precision Bearings Division, also located in Danbury, manufactures bearing rings. This division also assembles completed bearings.

The Precision Bearing Division is supported by component manufacturing at two other divisions. Lacey Manufacturing, located in Bridgeport, Connecticut, manufactures metal and phenolic bearing retainers. The Winsted Ball Company of Winsted, Connecticut, produces precision metal balls. The corporation has a second bearing manufacturing plant located in Plymouth, England. Barden U.K. Limited primarily manufactures miniature instrument bearings for the European market.

The company manufactures a wide variety of bearings. The bearings can be grouped into four product lines: miniature instrument bearings, spindle and turbine bearings, exotic bearings and aircraft bearings. The machine cells included in this study are used to grind spindle and turbine bearings.

Barden precision bearings are designed to operate at higher speeds with greater precision and under harsher environmental conditions than other bearings. As a result, an emphasis is placed on both product design and quality.

Like other domestic bearing companies, the Barden Corporation is experiencing competition from both foreign and domestic bearing manufacturers. In order to remain competitive, the company has adopted two manufacturing strategies: (1) produce high quality bearings at an affordable cost and (2) shorten the production time. This research is one part of a multi-faceted effort by the Barden Corporation to reduce both production time and costs.

All research and experimentation was performed on high precision machining cells at Barden's Danbury manufacturing facility. Currently, the company is implementing flow management technologies and operates four process/product lines. Although most bearings call for similar manufacturing processes, there is a significant amount of customer specification which can alter the order of operations.

Three different high precision machining operations were studied, inner ring bore grinding, outer ring race grinding and raceway honing. The machining operations performed in these areas were representative of those found in a high precision machine cell. The role of the cells in manufacturing a bearing is found in Section 3.5.1. Information about the inner ring bore grinding cell, the outer ring race grinding cell and the raceway honing cell can be found in Sections 3.5.2, 3.5.3 and 3.5.4, respectively.

3.5.1. Manufacturing a Ball Bearing:

The observed machine cells are used to manufacture a ball bearing. Figure 6 on page 46 defines the major components of a bearing. Additional information about bearing nomenclature can be found in Appendix A. The sequence of operations needed to machine, assemble and package a ball bearing is listed in Table 13 on page 45.

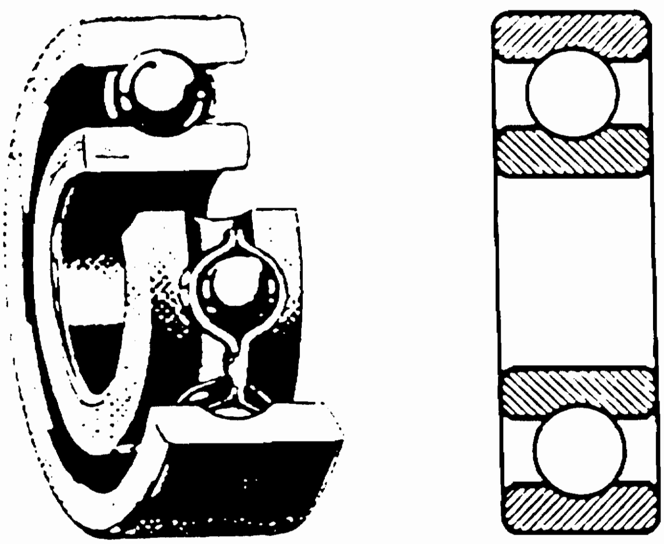
Table 13. Bearing Manufacturing Operations

	Operation
	1. Rough machining
	2. Secondary machining
	3. Heat treatment
•	4. Rough grinding
•	5. Finish grinding
•	6. Honing
	7. Polishing
	8. Tumbling
	9. Classification & matching
	10. Assembly
	11. Lubrication
	12. Packing

• Operations studied

The first two operations remove metal from bar stock. The end product is either a rough machined inner or outer ring. Lathes and CNC machines may be used to perform these operations.

The third operation is heat treating a part. The purpose of this operation is to strengthen the material of the rings. Because a bearing slightly deforms during the heat treat process and becomes difficult to cut, heat treatment is usually done after the heavy metal removing process and before the grinding operations.



This is what a ball bearing would look like if it had a slice cut out of it. The drawing on the right shows a ball bearing that has been cut in half.

Section view of an assembled deep-groove ball bearing

Figure 6. Components of a Bearing

Grinding is the process of removing metal from a part with an abrasive stone rotating at a high speed. The purpose of both rough and finish grinding is to bring a part within size and remove any imperfections (burrs). Finish grinding removes smaller amounts of material and improves the surface finish. Therefore, the average setup time for finish grind operations often takes longer than rough grind operations due to the tighter tolerances and greater sensitivity of the operation.

The next three operations, honing, polishing and tumbling, improve the surface finish of the bearings. Classification & matching pairs inner rings and outer rings. The purpose of this step is to group rings that have the most similar heights and raceway locations.

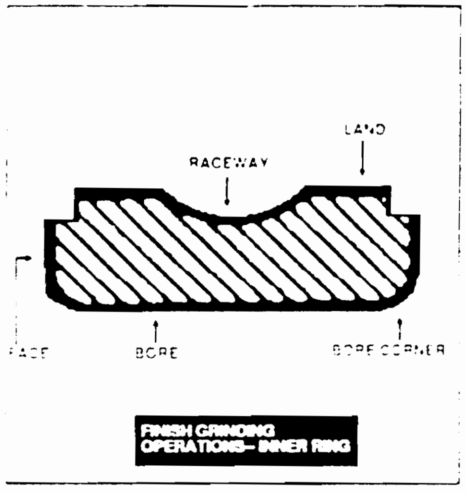
When a bearing is assembled, the metal balls, cages and shields are placed between an inner ring and outer ring. The bearing is assembled through heat and/or pressure. Also, based on a customer's request, different part components, lubrications and packaging can be used.

As shown in Table 13 on page 45, rough grind, finish grind and honing operations will be studied. These operations remove a small amount of material and have several tight tolerances. Therefore, they are considered to be high precision operations. Because it is impossible to grind or hone every dimension of a bearing simultaneously, each bearing has several machining operations. Figure 7 on page 48 depicts several rough and finish grinding operations.

3.5.2. Inner Ring Bore Grinding Cell:

The purpose of an inner ring bore grinder is to bring the bore size, the hole in an inner ring, to its correct dimension. There are two operations performed on the machines, rough grind and finish grind. Finish grind operations are completed after other manufacturing process are performed to correct any distortions caused by the other processes.

Finish grind operations can remove as little as 0.005" of material. Because there is little margin for error, this operation requires high precision. Extra inspection and setup tasks may be performed.



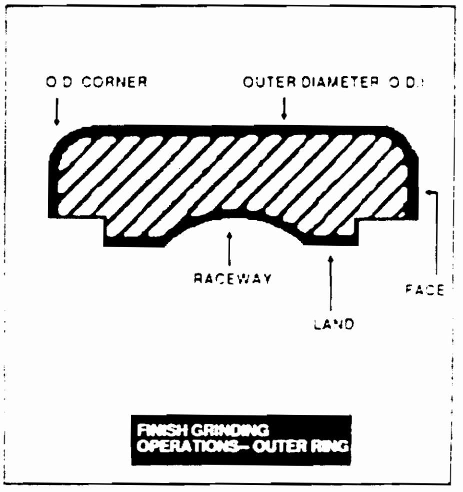


Figure 7. Grinding Operations

Also, there is more variation in average setup time for a finish grind operation than a rough grind operation.

The bore grinding machines are manufactured by the Bryant Corporation of Springfield, Vermont. The machines are named the Bryant Centerline 2s or Bryant C2s (Figure 8 on page 50).

The Bryant C2s remove burrs with a grinding stone rotating at a high speed. The parts are chute fed into and out of the machine. The minimum and maximum bearings OD sizes that can be ground on this machine are 1.588" and 4.435" respectively.

3.5.3. Outer Ring Race Grinding Cell:

The outer race grinding machines grind the raceway of an outer ring to its correct dimensions. There are two operations performed on these machines, rough and finish grind. Finish grind operations are completed after other manufacturing processes are performed to correct any distortions caused by the other processes.

Because several dimensions need to be measured, part inspection throughout a setup is critical. Also, the tolerances for finish grind operations are tighter than rough grind operations. For some dimensions, the allowed tolerances can be as small as 0.0001". Therefore, because of the tight tolerances and the number of checked dimensions, finish grinding requires high precision.

There are two different race grinders included in the research study, the Heald 1EF91 and Heald 1CF91 (Figure 9 on page 51). Both machines are manufactured by the Cincinnati Heald Corporation of Worcester, Massachusetts. The difference between the machines is their power source. The 1CF91 machines use a hydraulic motor while the 1EF91 machines use an electric motor. Both machines have identical tooling and setup procedures.

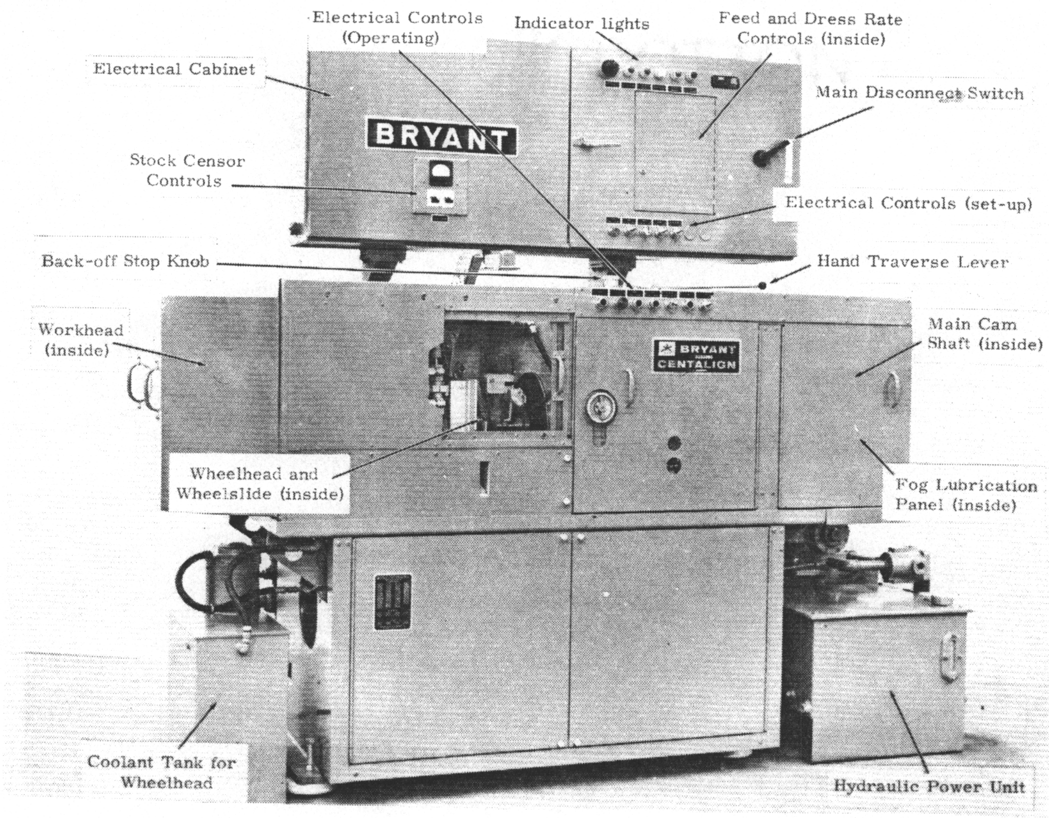


Figure 8. Bryant Centerline 2 Bore Grinder

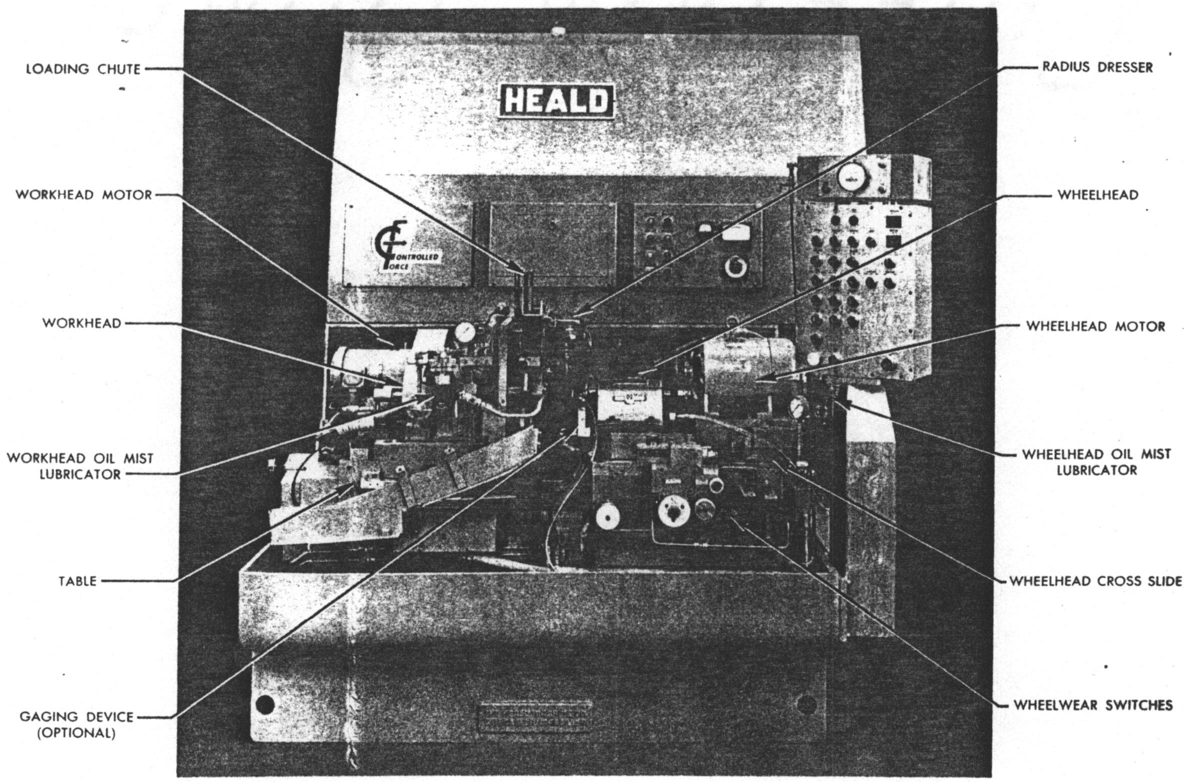


Figure 9. Heald 1CF91 Race Grinder

Both machines remove burrs from a raceway with an abrasive wheel which is rotating at a high speed. Like the bore grinders, parts are loaded and unloaded through chutes. The range of parts that can be run on this machine are from 0.875" to 4.500" in diameter.

3.5.4 Raceway Honing Cell:

The raceway honing cell removes any small burrs and improve the surface finish of a bearing ring. Both inner ring and outer ring bearings can be honed on the same machine. Honing is the last manufacturing operation before the bearings are assembled.

Because honing is the last manufacturing operation, part inspection is critical. The tolerances on these parts are tighter than other operations. Also, a number of special inspection tests, completed away from the machines are performed.

The honing machines are manufactured by the Thielenhaus Corporation of Switzerland. The machines are named the Microfinish KM85. There are four machines in the cell (Figure 10 on page 53). Each machine can hone both inner and outer ring bearings. For both types of bearing rings, the same setup procedure and style of tooling are used. Although the size of some tooling varies for an inner ring and an outer ring, there is no noticable change in the setup time or procedure.

The honing machines remove material from a bearing with a fine grit honing stone. The machines use a four position turret to hone a part. At the first position, a part is loaded via a loading chute. Positions 2 and 3 are the machining operations. At the fourth position, the bearing is unloaded via an unloading chute. The minimum and maximum bearing outer diameter sizes that can be honed on these machines are 1.024" and 3.349".

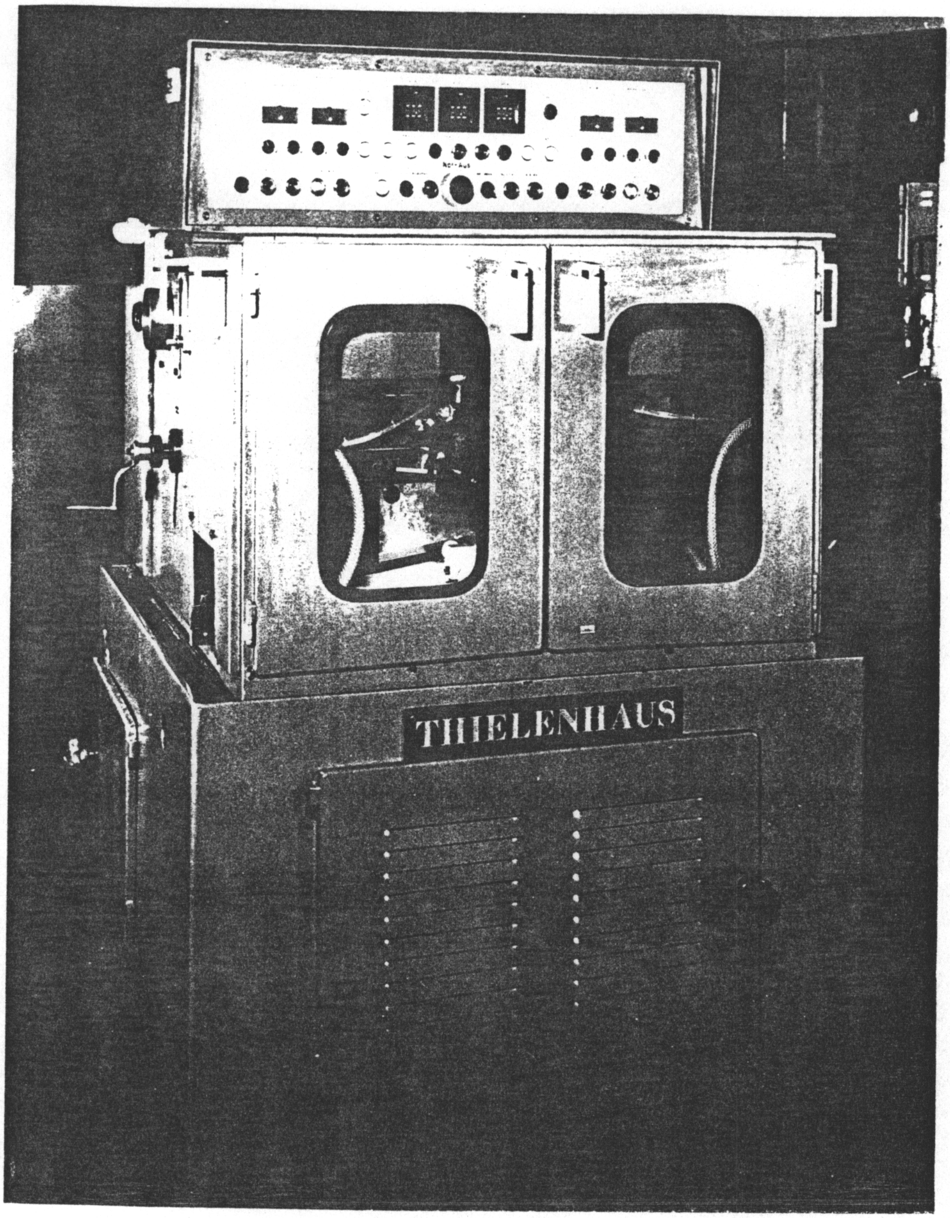


Figure 10. Thielenhaus Honing Machine

Chapter 4

Evaluation of an Existing Setup Reduction Method

4.0 Overview

A study was conducted to determine the strengths and weaknesses of an existing setup reduction method in high precision machine cells. The study consisted of two parts. First, the Single Minute Exchange of Dies (SMED) method for reducing setup time was evaluated in two high precision machine cells. Second, problems in such cells which contributed to setup time variation were documented and analyzed.

Several writers claim that SMED reduces setup time from 70 to 90 percent. The method consists of three phases: separating internal and external elements, converting internal elements into external elements and simplifying all elements. After completing each phase, the setup time is allegedly reduced by 30 - 50%, 25% and 15%, respectively.

SMED was tested in two different high precision machining cells. In general, the basic concepts of SMED could be applied to most machine cells. However, on an individual machine basis, there were portions of SMED which could not be implemented. As a result, the stated claims for one phase of SMED was accepted in one cell, but rejected in another. It appeared that the original changeover procedures, the condition of the equipment, the machine design, and the project motivation were controlling variables that determined the success of SMED. Setup time was greatly reduced if equipment could be interchanged or subassembled. If the existing setup procedure was efficient and if equipment could not be interchanged, the resulting reduction in setup time was small. Further discussion about the evaluation of SMED is presented in Section 4.1.

Although SMED reduced setup time, a number of related problems were not corrected. As a result, there was still variation in completing a machine changeover. A data set was collected over a one month period. Besides random machine/tooling failures, two types of problems were not addressed by SMED. First, tasks performed away from the machine area were not simplified. Second, labor related problems were not directly addressed. These two types of delays accounted for approximately 15 percent of the total machine changeover time. Further discussion about causes and effects of these problems is presented in Section 4.2.

4.1 Evaluation of SMED

The Single Minute Exchange of Dies (SMED) method of setup reduction was evaluated in two high precision machine cells. The objectives of the study were to (1) determine if the method reduced setup time, (2) show if the actual results were similar to the stated reduction claims, (3) determine if there were portions of SMED which were not applicable to high precision machine cells and (4) determine if there were problems which were not addressed.

SMED consists of three phases. The first phase is to identify and separate internal and external elements. There are two claims for the expected percent reduction of Phase 1. Shingo claims that the total setup time can be reduced by 30 - 50 percent. Another author, Productivity Inc., claims that a 50 percent reduction can be expected. The second phase is to convert internal elements into external. It is claimed that this step reduces the total setup time by 25 percent. The final phase is to simplify both internal and external elements. It is claimed that Phase 3 reduces setup time by 15 percent.

Throughout the evaluation of SMED, data sets were collected and analyzed (Table 14). The average machine down time in both cells was reduced. However, the anticipated 70 to 90 percent reduction claim was not obtained in either cell. In the race grinding cell, setup time was reduced by 42%. In the bore grinding cell, setup time was lowered by 67%.

The resulting reduction in setup time for each phase of SMED also varied. The 30 or 50 percent reduction claim of Phase 1 was not obtained in either cell. For Phase 2, the expected 25 percent reduction claim was obtained in the both cells. Finally, the expected 15 percent reduction after completing Phase 3 was not obtained in either cell.

Table 14. Setup Time Reduction Summary

		Bore Grinding Cell		Race Grinding Cell	
Phase	Expected Reduction	Actual Average	% Reduction	Actual Average	% Reduction
0	----	8.13	-----	5.94	-----
1	30-50%	6.41	21.2	5.50	7.4
2*	25%	3.37	37.4	3.74	29.6
3*	15%	2.58	9.7	3.28	7.7

* In both areas, a smaller sample size was used (n = 10).

Statistical tests were also performed to compare the actual results with the stated claims. Tests were conducted which used the average setup time and the standard deviation after completing each phase of SMED. For Phase 1, the 50% reduction claim in setup time was statistically rejected in both cells. Also, the 30% reduction claim for Phase 1 was statistically accepted in the bore grinding cell, but not in the race grinding cell. The 25% reduction claim for Phase 2 was statistically accepted in both cells. Finally, the 15% reduction claim for Phase 3 was statistically accepted in the race grinding cell, but not in the bore grinding cell. The assumptions, formulas and calculations for these tests are defined in Sections 4.1.b - 4.1.d.

Three conclusions were drawn from the results of the study. First, each phase of SMED contributed to the overall reduction in setup time. Second, the resulting percent reduction in setup time varied and the stated reduction claims were not always obtained. Third, after implementing SMED, there was still a significant amount of setup time variation. This indicated that a number of setup problems still existed.

Four reasons were identified for the varied results of each phase of SMED: (1) the original changeover procedure, (2) the condition of the equipment, (3) the machine design, and (4) the motivation required to implement an idea. If the original changeover procedure is efficient, the benefits of implementing Phase 1 may not be significant. For example, if a number of setup tasks are already completed while the machine is running, the expected reduction in setup time by separating internal elements from external elements will not be substantial. The condition of the equipment was another variable. If the equipment is in poor condition, tooling or machine failures will occur. As a result, machine changeovers are prolonged. Another variable is the machine design. Setup time can be significantly reduced if machinery is designed so that there are a number of subassemblies or interchangeable tooling. It was found that with additional tooling, subassemblies can be built while a machine is running. Therefore, the resulting reduction in setup time after implementing Phases 1 and 2 will be significant if this type of equipment exists. Finally, although a number of ideas to reduce setup time can be generated at each phase, implementing them can be difficult. Ideas must be sold to all levels of management and to the setup operators. If there is not enough motivation in any group, the success of implementing a portion of SMED is jeopardized.

The evaluation of each phase of SMED in both grinding cells is presented in Section 4.1.a - 4.1.d. Since there was still a significant amount of variation after implementing SMED, a study was conducted to determine the causes and effects of these problems. The results of this study are presented in Section 4.2.

4.1.a Phase 0 - Documenting the Current Procedure:

SMED was evaluated in an inner bore grinding and outer ring race grinding cell. Initially, a data set was taken from company records to determine the initial average setup time in both areas (Table 15). Partial setups and reworked lots were not included in the data set. All times are in hours.

Table 15. Initial Machine Setup Time - Bore and Race Grinding Cells

	Bore Grinding Cell			Race Grinding Cell	
	MACHINE 1	MACHINE 2	MACHINE 3	MACHINE 1	MACHINE 2
Mean	8.51	8.06	7.50	6.39	5.48
Std. Dev.	3.24	2.91	2.90	2.78	2.18
Sample Size	30	30	30	30	30

The average setup time and the standard deviation for each machine were calculated. Although each machine within a cell uses the same tooling, procedures and personnel, it was desired to statistically prove if the machine data could be combined. If the data could be pooled, future studies would be conducted assuming that data collected from any machine represented the machine cell as a whole.

The difference in means test was selected to determine if machine data could be pooled. This test determines if the difference between the means of two samples is near zero. If this difference is within the critical limits, the data sets are similar. The test can assume that the true standard deviations are either equal or unequal. It was assumed that since each machine in a cell use the same tooling design, personnel and processes, the true standard deviations were unknown, but equal. The formulas and calculations are presented below.

μ_{ij} = Mean setup time for machine i at time j

s_{ij} = Standard deviation in setup time for machine i at time j

n_{ij} = Sample size for machine i at time j

t = Test statistic

s_p = Pooled standard deviation for two samples

α = Probability of rejecting a valid hypothesis

v = Degrees of freedom

Hypothesis Tests:

$H_0 = \mu_{i1} - \mu_{i'1} = 0$

$H_1 = \mu_{i1} - \mu_{i'1} \neq 0$ where i' = Another machine in the same cell as machine i

Critical Region at $\alpha = 0.05$:

$t < -t_{\frac{\alpha}{2}} = -1.960$

$t > t_{\frac{\alpha}{2}} = 1.960$

Formulas (given $\sigma_{ij} = \sigma_{i'j}$)

$$t = \frac{(\bar{x}_{ij} - \bar{x}_{i'j})}{s_p\sqrt{\frac{1}{n_{ij}} + \frac{1}{n_{i'j}}}} \quad [4.1]$$

$$v = n_{ij} - n_{i'j} - 2 \quad [4.2]$$

$$s_p^2 = \frac{(n_{ij} - 1)s_{ij}^2 + (n_{i'j} - 1)s_{i'j}^2}{n_{ij} + n_{i'j} - 2} \quad [4.3]$$

Bore Grinder Calculations:

For machines 1 and 2,

$$s_p = \frac{(30-1)3.24^2 + (30-1)2.91^2}{30 + 30 - 2} = 3.082$$

$$t = \frac{8.51 - 8.06}{3.082\sqrt{\frac{1}{30} + \frac{1}{30}}} = 0.5655$$

$$v = 30 + 30 - 2 = 58$$

For machines 2 and 3, $s_p = 2.907$ $t = 0.7461$ $v = 58$

For machines 1 and 3, $s_p = 3.079$ $t = 1.2704$ $v = 58$

Decision: Do not reject H_0

Race Grinder Calculations:

For machines 1 and 2, $s_p = 2.499$ $t = 1.4103$ $v = 58$

Decision: Do not reject H_0

The tests proved that data within the same machine cell could be combined. When the data sets were pooled together, the average setup time for a machine in the inner ring bore grinding cell is 8.14 hours with a standard deviation of 3.02 hours. The average setup time for a machine in the outer ring race grinding cell is 5.93 hours with a standard deviation of 2.52 hours. Histograms of the documented setup times for both cells are shown in Figure 11 on page 61. Table 16 presents relevant statistics about the distribution of setup time for both cells.

Table 16. Revelant Setup Time Statistics - Phase 0

Variable	Bore Cell	Race Cell
Sample Size	90	60
Average	8.13	5.93
Median	7.85	5.10
Mode	5.40	4.60
Variance	9.14	6.25
Standard Deviation	3.02	2.50
Minimum	3.3	2.7
Maximum	15.3	12.1
Range	12.0	9.4
Skewness	0.68	0.78

The setup procedure for both the bore and race grinding cells was observed and documented to identify the order and length of each setup task. The results were discussed with various setup operators to establish standard setup procedures. The accepted changeover procedure for both bore and race grinding machines are listed in Table 17 on page 62, and Table 18 on page 63, respectively. The tables list each element and its standard completion time. The standard time assigned to each element represents how much time is needed to complete the task, assuming that no interruptions or problems occur.

The total standard time in the bore grinding cell was 4.0 hours. In the race grinding cell, the total standard time was 3.6 hours. The reason for the difference between the standard and average time is due to the variation in completing some setup tasks. The effects of variation can be seen in the histogram of setup times (Figure 11 on page 61). Both curves are skewed. Also, because the standard times are closer to the modal point of both distributions than the average setup time, it was concluded that the average setup time increases when variation is large.

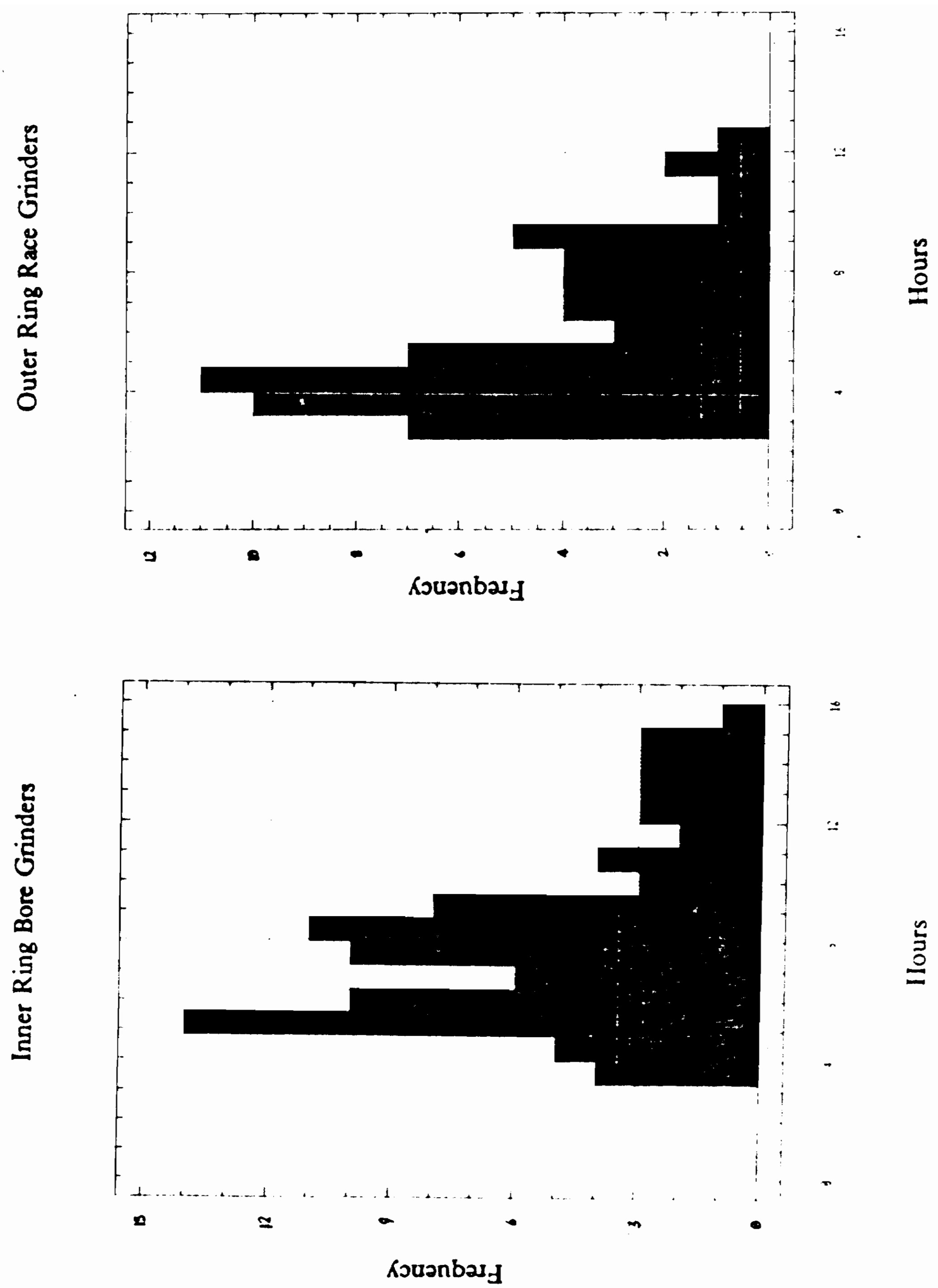


Figure 11. Initial Setup Time Histogram Plots - SMED Evaluation

Table 17. Standard Setup Procedure - Inner Ring Bore Grinders

#	STEP	STANDARD TIME
1	Complete paperwork. Get parts. Get tooling	12
2	Get spindle	10
3	Get gaging	2
4	Contact gage setter Count and remove old lot	2 15
5	Remove guards, main unit, driver and internal gage	6
6	Set shoes	10
7	Build main unit	14
8	Change spindle	10
9	Install and indicate driver	15
10	Set stroke	15
11	Install main unit and align driver to unit	12
12	Install new wheel. Align wheel to part. Set diamond. Set wheel indicators.	30
13	Set, install and adjust internal gage	33
14	Set and install loaders. Return covers.	10
15	Get part within size. Grind 25 good parts.	25
16	Check-in (by area lead man)	10
17	Return old tooling and gaging	8

Table 18. Standard Setup Procedure - Outer Ring Race Grinders

#	STEP	STANDARD TIME
1	Complete paperwork. Get parts. Get tooling	12
2	Get spindle	10
3	Get gaging	2
4	Count and remove old lot	15
5	Set loaders Set shoes	10 10
6	Remove old tooling	5
7	Set dresser Set workhead	7 5
8	Install spindle Install new tooling	10 30
9	Center new wheel to part	5
10	Align diamond and new wheel	8
11	Dress off new wheel	8
12	Find size and location	12
13	Install loaders	10
14	Grind part within tolerances	20
15	Return old lot Bring part sample for burn-in inspection	5 5
16	Grind 25 parts and clean area	8
17	Check-in (by area lead man)	10
18	Return old tooling and gages	8

4.1.b Phase 1 - Separating Internal and External Elements:

Phase 1 of SMED is to separate internal elements from external elements. Internal elements are those tasks which must be done while the machine is stopped. External elements are tasks which can be completed while a machine is running. It is claimed that a 30 to 50 percent reduction in setup time occurs when these tasks are separated.

Phase 1 of SMED was tested in both machine cells. In the bore grinding cell, element numbers 1, 2, 3, 4 and 17 (see Table 17 on page 62) were found to be external. In the race grinding cell, elements 1, 2, 3, 4 and 18 were external (see Table 18 on page 63). If these tasks were completed while the machines were running, approximately 49 minutes could be saved in the bore grinding cell and 47 minutes in the race grinding cell. This would represent a 20% reduction on the bore grinders and a 22% reduction on the race grinders.

Attempts were made by setup operators to complete all external elements before a machine stopped running a lot. A data set was collected and analyzed. The average setup time in the bore grinding was 6.41 hours (a 21.2 % reduction) with a standard deviation of 2.38 hours. In the race grinding cell, the average setup time was 5.50 hours (a 7.4 % reduction) with a standard deviation of 2.66 hours. A Student T test was used to statistically prove if either the 30 or 50 percent reduction claims were met. The tests proved if the difference between the mean setup time of Phase 1 and Phase 2 was equal to 30 or 50 percent of the original setup time. The tests used a 95% confidence level, (α = 0.05). Also, the tests assumed that the true standard deviations were unknown and unequal. They were assumed unequal because the setup procedures had changed. The formulas and calculations for this test are presented below.

Notation:

μ_k = Mean setup time at time k

s_k = Standard deviation in setup time at time k

n_k = Sample size at time k

d_0 = Expected difference (i.e. 30% of the original setup time)

t = Test statistic

α = Probability of rejecting a valid claim

ν = Degrees of freedom

k = Current phase of SMED

j = Prior phase of SMED (k - 1)

Hypothesis Tests:

$H_0 = \mu_k - \mu_j = d_0$

$H_1 = \mu_k - \mu_j = d_0$

Critical Region at $\alpha = 0.05$:

$t < -t_\alpha = -1.645$

Formulas (given $\sigma_k \neq \sigma_j$)

$$t = \frac{(\bar{x}_k - \bar{x}_j) - d_0}{\sqrt{\frac{s_k^2}{n_k} + \frac{s_j^2}{n_j}}} \qquad [4.4]$$

$$\nu = \frac{\left(\frac{s_k^2}{n_k} + \frac{s_j^2}{n_j}\right)^2}{\frac{\left(\frac{s_k^2}{n_k}\right)^2}{n_k - 1} + \frac{\left(\frac{s_j^2}{n_j}\right)^2}{n_j - 1}} \qquad [4.5]$$

Bore Grinder Calculations:

For the 30 percent claim,

$$\nu = \frac{\left(\frac{3.0^2}{30} + \frac{2.4^2}{30}\right)^2}{\frac{\left(\frac{3.0^2}{30}\right)^2}{29} + \frac{\left(\frac{2.4^2}{30}\right)^2}{29}} = 55.0$$

$$t = \frac{(8.1 - 6.4) - (.30)8.1}{\sqrt{\frac{3.0^2}{30} + \frac{2.4^2}{30}}} = -1.109$$

For the 50 percent claim, $t = -3.337 \quad \nu = 55.0$

Decisions: Do not reject H_0 for the 30 percent claim

Reject H_0 for the 50 percent claim

Race Grinder Calculations:

For the 30 percent claim, $t = -2.005 \quad v = 57.8$

For the 50 percent claim, $t = -3.770 \quad v = 57.8$

Decision: Reject H_0 for the 30 percent claim

Reject H_0 for the 50 percent claim

In both the bore and race grinding cells, the 50% reduction claim was rejected. However, the 30% reduction claim was accepted in the bore grinding cell, but not in the race grinding cell.

There appears to be three reasons why the anticipated reduction in setup time after completing Phase 1 varies. First, the number and length of external elements vary from machine to machine. Although the number of external tasks in the bore and race grinding areas are similar, it is unlikely that every machine has the same number of external tasks. Also, it is unlikely that the length of these tasks is the same for each machine. The original setup procedure and policies can also affect the resulting reduction in setup time. In the race grinding cell, an area lead man ensured that all tool orders were completed in advance. In the bore grinding cell, less effort was made. As a result, more opportunities to separate external elements from internal elements existed in the bore grinding cell than in the race grinding cell. Therefore, Phase 1 was more beneficial in the bore grinding cell. The final reason for the varied results is the process of completing some external elements, such as getting tooling and gages, were not totally controlled by the setup operator. If these elements were not completed in a timely manner, delays occurred. In the race grinding cell, there were more off-site elements than in the bore grinding cell. Because some setup delays still occurred, the benefits of Phase 1 were not as significant as anticipated.

4.1.c Phase 2 - Converting Internal Elements into External:

Phase 2 of SMED identifies what tasks, which currently must be done while a machine is stopped, can be modified so that they can be performed while a machine is running. Two methods to convert internal elements into external elements are to purchase additional equipment or to standardize the functions of some tooling. It is claimed that after completing Phase 2, machine down time is reduced by 25%.

Phase 2 was tested in both machine cells. In the inner ring bore grinding cell, a part holding device (the shoes), a loading mechanism (the main unit) and an internal machine gage could be preset if additional equipment were available. In the outer ring race grinding cell, the shoes and a loader could be preset. Additional loaders and shoes were already available. However, because some of the loaders and shoes were in poor conditions, equipment failures were common. Also, because replacements were not always available, they could not regularly be preset. Table 19 lists the time saved and the rough cost to implement each idea.

Table 19. SMED Evaluation - Phase 2 Improvements

- **Bore Grinding Cell:**

PROPOSAL	SAVINGS	COST
1. Repair shoes so that presets are possible	10 min.	$0
Build a second shoe setting fixture		$600
2. Build a second main unit (in house)	14 min.	$15,000
3. Purchase a second internal gage	15 min.	$20,000

- **Race Grinding Cell:**

PROPOSAL	SAVINGS	COST
1. Repair shoes so that presets are possible	10 min.	$0
2. Repair loaders so that they can be preset	10 min.	N/A

If all three proposals in the bore grinding cell were implemented, the machine down time would be reduced 39 minutes or 16.25% of the original 239 minute setup. In the race grinding cell, machine down time would be reduced 20 minutes or 9.30% of the original 215 minute setup time. For both cells, the anticipated 25% reduction in machine down time could not be obtained.

The proposed ideas were tested in the machine cells. The suggested improvements were shown to be feasible. Shoes were preset and a second loading mechanism was borrowed from another machine in the cell. Both items could also be preset and interchanged. Ten machine setups were documented. For each setup, the total time saved by having such tooling or equipment permanently available was calculated. The results of the study indicated that the average setup time, after completing Phase 2, would be 3.37 ± 0.552 hours in the bore grinding cell (a 37.4% reduction in setup time) and 3.74 ± 1.59 hours in the race grinding cell (a 29.6% reduction in setup time). A hypothesis test was then performed to validate the original 25 percent claim. The assumptions used for these tests are the same as Phase 1. The formulas and calculations for these tests are shown below.

Bore Grinding Cell:

Critical Region at $\alpha = 0.05$

$t < -t_{\alpha} = -1.645$ given $\nu = 30.2$

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -1.109 ν = 30.2

Decision: Do not reject H_0

Race Grinding Cell:

Critical Region at $\alpha = 0.05$

$t < -t_{\alpha} = -1.705$ given $\nu = 26.5$

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -0.600 ν = 26.5

Decision: Do not reject H_0

In both the bore and race grinding cells, the 25% reduction claim was statistically accepted. There are three reasons why the claims were obtainable in a real world application. First, repairing equipment may have reduced some of the variability in installation time. Second, operators, seeing equipment repaired or ordered, may have been more motivated. Third, because the operators knew that a setup study was occurring, extra efforts were probably made to avoid any idle/wait time. For Phases 0 and 1, company records were used to develop the data sets. For Phases 2 and 3, direct observation was used. Because a smaller sample size was used, some problems contributing to the overall variation may have been missed.

The resulting reduction in setup time after completing Phase 2 varied between the bore grinding and race grinding cell. The main reason for this difference is the number and length of internal tasks which could be converted into external elements. In the bore grinding cell, the preparation of a loading unit, an internal gage and a part holding device could become external elements. However, in the race grinding cell, only the loaders and a part holding device could become external elements. One reason why some machines have more potential external elements than others is their design. Modern machinery is often designed for greater flexibility by including interchangeable equipment and subassemblies. With this type of machinery, setup time can be easily reduced by completing these subassemblies in advance. It was noted that the machinery in the bore grinding cell, (purchased between 1974 - 1979), appeared to be designed for more flexibility than the race grinding machines, (purchased between 1967 - 1973.)

4.1.d. Phase 3 - Streamline Internal and External Elements:

Phase 3 of SMED is to simplify all setup tasks. There are three methods that can be used. First, quick release clamps can be substituted for the traditional nut and bolt clamps. Second, preset stops or calibrations can be placed on objects that are adjusted. Finally, using additional labor can shorten the time needed to complete setup tasks. Different authors (Shingo, Productivity) state that the total setup time can be reduced 15 percent by streamlining both internal and external elements.

Each method was considered in both the inner ring bore and outer ring race grinding machine cells. Quick release clamps were installed in non-critical areas. Approximately five minutes was saved by using these clamps. In other areas, quick release clamps could not be installed for a number of reasons. First, some quick release clamps could not provide a acceptable clamping force (i.e. on a spindle motor). Second, space limitations existed which prevented larger clamps from being implemented. Third, some clamps would have caused functional problems. For example, a hydraulic clamp was once considered to hold a spindle. Because the clamp had hydraulic lines and would have been mounted to a moving feed block, it could not be used.

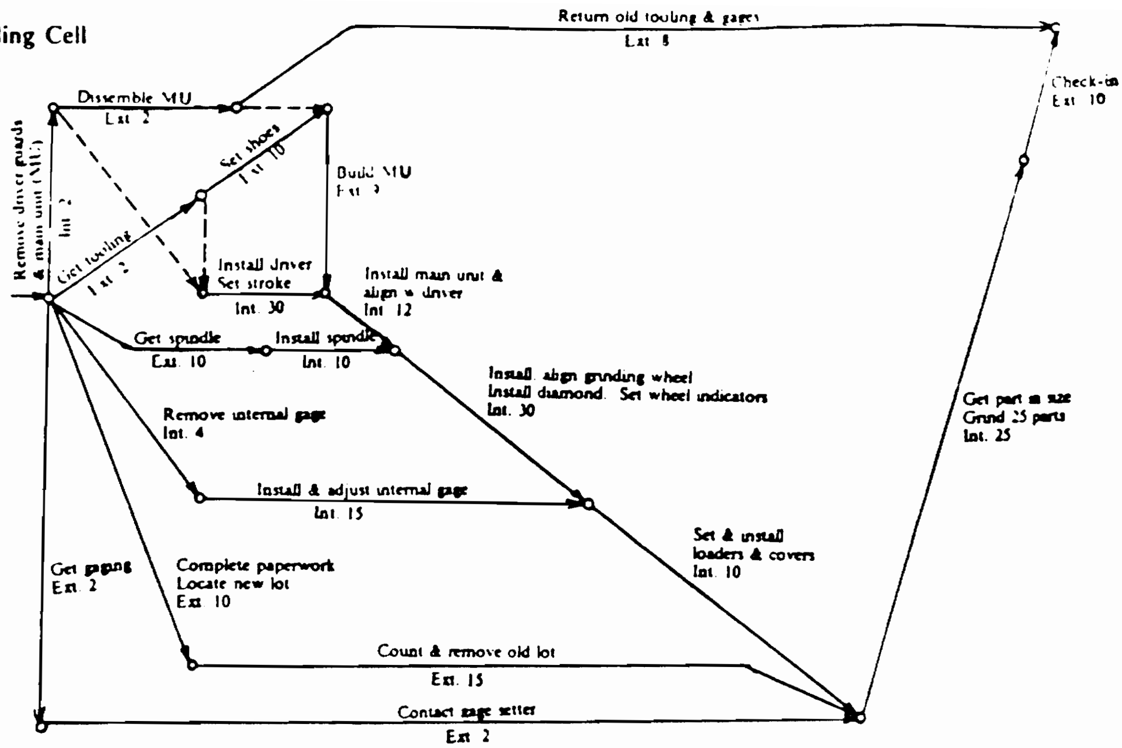
Installing preset stops or calibrations were considered in both machine cells. A number of settings are needed on the items that require adjustments. Also, the company that participated as a case study regularly introduces new, custom designed parts which may require a distinct machine setting. Therefore, because a wide range of settings is needed and space limitations, it was infeasible to install preset stops. Calibrations were already present on some items in the machines. For other items, there was not enough available space to place any markings.

The third method to simplify changeover tasks is to have more than one operator setup a machine. The operators can perform different tasks simultaneously or work together on the same job. This approach in reducing setup time was considered in both the inner ring bore and outer ring race grinding cells. In both cells, a network diagram of the setup process was prepared (Figure 12 on page 71). Each line represents a setup task. Each circle, or node, represents a point in time. Before beginning any tasks that exit a node, all tasks entering the node must be completed.

The network diagrams were used to create schedules for two operator setups (Table 20 on page 72 and Table 21 on page 73) in both machine cells. These schedules indicate when each task should be performed. The schedules also state how long each task takes to complete. The total machine down time for the bore grinding machines was hypothetically reduced by 0.50 hours or 12.5% of the original 4.0 hours. For the race grinding machines, the setup time should be reduced by 0.25 hours or 7.0% of the original 3.6 hours. Therefore, the 15 percent reduction claim was hypothetically rejected in both cells.

The proposed setup reduction schedules were tested in the machine cells. First, it was shown that two operator setups were feasible. The operators were able to complete their tasks on schedule. Also, the operators did not interfere or interrupt each other's work. Second, both operators were able to keep busy. In both areas, a second operator was not needed for the entire setup. After completing the required tasks, they could leave the work area.

Bore Grinding Cell



Race Grinding Cell

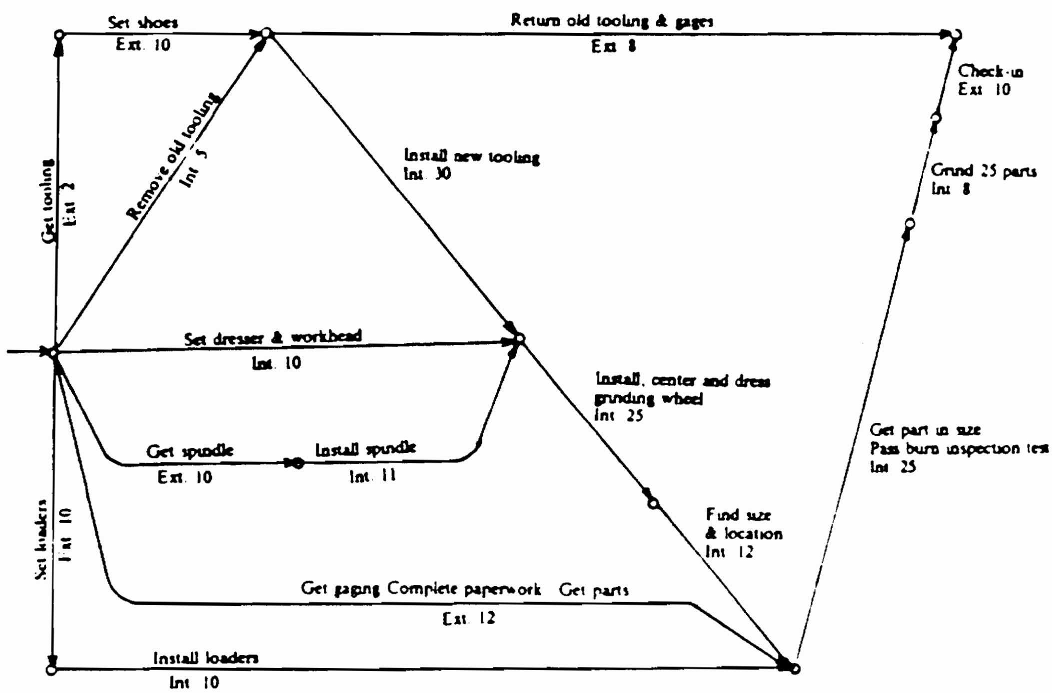


Figure 12. Line and Node Charts - Bore and Race Grinding Machines

Table 20. Multiple Setup Operator Schedule - Bore Grinding Cell

WORKER 1			WORKER 2		
#	STEP	STND. TIME	#	STEP	STND. TIME
1	Complete paperwork. Get parts & tooling	12		PRODUCTION	
2	Get spindle	10			
3	Get gaging	2			
4	Assemble shoes and main unit	19			
5	Contact gage setter	2	1	Remove main unit and driver Change spindle	2 10
6	Remove & externally set the internal machine gage	20	2	Install and indicate driver	15
7	Set loaders	5	3	Set stroke	15
8	Remove tooling from the old main unit & return tooling	8	4	Install new main unit	2
9	Count and remove old lot	15	5	Align wheel w/ part. Set diamond & wheel indicators	30
			6	Install & adjust internal gage	15
			7	Install loaders and covers	5
			8	Get part within tolerances and grind 25 good parts	25
			9	Check-in (by area lead man)	10

Table 21. Multiple Setup Operator Schedule - Race Grinding Cell

WORKER 1			WORKER 2		
#	STEP	STND. TIME	#	STEP	STND. TIME
1	Complete paperwork. Get parts & tooling	12			
2	Get spindle	10			
3	Get gaging	2		PRODUCTION	
4	Set shoes	10			
5	Set loaders	10			
6	Set workhead	5	1	Remove old tooling	5
7	Count and remove old lot	15	2	Set dresser	7
8	Return old tooling and gages	8	3	Install spindle Install new tooling	10 30
			4	Center wheel to part	5
			5	Align diamond and new wheel	8
			6	Dress off new wheel	8
			7	Find size and location	12
			8	Install loaders	10
			9	Get part within tolerances	20
			10	Bring part sample for burn inpection	5
			11	Grind 25 good parts	8
			12	Check-in (by area lead man)	10

Additional tests were performed to validate the stated 15 percent reduction claim of the third phase of SMED. Because the company that is participating in the case study does not have enough manpower to permanently adopt this policy, the data set was modified to simulate a two operator setup. Specifically, elements which would have been done by a second operator were subtracted from the total setup time. Figure 13 on page 75 demonstrates how the data set for Phase 3 was derived. The results of the study showed that the average setup time, after completing Phase 3, would be 2.58 ± 0.450 hours in the bore grinding cell (a 9.7 percent reduction) and 3.28 ± 0.263 hours in the race grinding cell (a 7.7 percent reduction). A hypothesis test was then performed to validate the original 15 percent claim. The formulas and calculations for these tests are shown below.

Bore Grinding Cell:

Critical Region at $\alpha = 0.05$

$t < -t_{\alpha} = -1.738$ given $v = 17.3$

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -1.911 v = 17.3

Decision: Reject H_0

Race Grinding Cell:

Critical Region at $\alpha = 0.05$

$t < -t_{\alpha} = -1.846$ given $v = 9.5$

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -0.846 v = 9.5

Decision: Do not reject H_0

In the race grinding cell, the 15% reduction claim was statistically accepted. In the bore grinding cell, the 15% claim was rejected. However, because the difference between the critical value and test statistic was small (0.173 or 9.9%), a sensitivity test was performed. If the average time in the bore grinding cell was reduced to 2.54 hours (an additional 0.04 hours or 2.4 minutes) or if the standard deviation was 0.555 hours, the 15% reduction claim would have been accepted. Therefore, it was concluded that the 15% reduction claim in the bore grinding area was almost accepted.

Inner Ring Bore Grinders

Because labor constraints existed, phase 3 could not be permanently implemented. Data from phase 2 was altered to determine the resulting down time if phase 3 was fully implemented. Actual data was modified by identifying what tasks would have been completed by a second operator and subtracting them from the total machine down time. An example is provided below. All documented times are in minutes.

Assumptions:

1. All external elements can be completed by worker #2 while worker # 1 operates the machine.
2. Worker #2 can prepare the internal machine gage and set the loaders without interfering worker #1.
3. Worker #2 ensures that all goods are available at the start of a changeover.

Phase 2		Phase 3			
Worker #1		Worker #1		Worker #2	
Step	Time	Step	Time	Step	Time
Contact gage setter,	2	Remove main unit, driver and guards	2	Contact gage setter	2
Count & remove old lot	15				
Remove main unit, driver, guards & internal gage	6	Change spindle	10	Remove & externally set internal gage	19
Change spindle	10	Install, indicate driver	15	Set loaders	5
Install, indicate driver	15	Set stroke	15	Remove and return tooling from the former main unit	8
Set stroke	15	Install MU & align driver	12	Count & remove old lot	15
Install MU & align driver	12	Set & align wheel driver and indicators	30		
Set & align wheel driver and indicators	30	Install & adjust internal gage	15		
Set, install & adjust internal gage	33	Install loaders, covers	10		
Set and install loaders & covers	15	Get part in size Grind 25 parts	25		
Get part in size Grind 25 parts	25	Check-in	10		
Check-in	10				
Total down time	**188**	**Total down time**	**139**		

Outer Ring Race Grinders

Because labor constraints existed, phase 3 could not be permanently implemented. Data from phase 2 was altered to determine the resulting down time if phase 3 was fully implemented. Actual data was modified by identifying what tasks would have been completed by a second operator and subtracting them from the total machine down time. An example is provided below. All documented times are in minutes.

Assumptions:

1. All external elements can be completed by worker #2 while worker #1 operates the machine.
2. Worker #2 can set the workhead without interfering worker # 1
3. Worker #2 ensures that all goods are available at the start of a changeover

Phase 2		Phase 3			
Worker #1		Worker #1		Worker #2	
Step	Time	Step	Time	Step	Time
Remove old tooling	5	Remove old tooling	5	Set workhead	5
Count & remove old lot	15				
Set dresser	7	Set dresser	7	Count & remove old lot	15
Set workhead	5	Install spindle	10		
Install spindle	10	Install new tooling	30		
Install new tooling	30	Center wheel to part	5		
Center wheel to part	5	Align diamond	8		
Align diamond	8	Dress off wheel	8		
Dress off wheel	8	Find size & location	12		
Find size & location	12	Install loaders	10		
Install loaders	10	Get part in size	20		
Get part in size	20	Bring part sample to inspection	5		
Bring part sample to inspection	5	Grind 25 parts	8		
Grind 25 parts	8	Check-in	10		
Check-in	10				
Total down time	**158**	**Total down time**	**138**		

Figure 13. Data Collection Procedure - Phase 3 of the SMED Evaluation

There are two reasons why the actual results of Phase 3 differ from the hypothetical results. First, the second operator ensured that all tooling, gages, incoming work and preset equipment were at the machine area before production stopped. These tasks contribute to setup time variation if delays occur. Since the second operator was able to give full attention to these tasks, idle and wait time were minimized. Second, the operators were able to pace each others work.

4.2 Identification of the Causes and Effects of Setup Time Variation

Table 14 on page 56 shows the actual average changeover time throughout each phase of the setup reduction project. The table also shows that there is a significant amount of variation in setup time. As shown in Figure 11 on page 61, when the variation is great, the average setup time moves away from the modal point, the most common setup time. For example, in the bore grinding cell, the most common setup time was 5.4 hours. However, because there were a number of long setups, the average setup time became 8.13 hours.

After implementing SMED, the average machine changeover time and the standard deviation were reduced. However, in both areas, the standard deviation was still significant. A study was then conducted to determine what caused setup time variation. Three issues were addressed. First, a rough measure was defined to determine if the variation in completing a setup element was reasonable. Second, it was shown whether internal, external or both types of elements caused the variation. Finally, the causes of variation were identified and shown to be either unique to the cell, the operation or the machine.

The total machine setup time is the sum of the completion time for each element. For each element or task, an average time and standard deviation is calculated. If a task is out of control, the expected completion time covers a wide range of values. If the task is in control, the anticipated completion time should not vary far from the average time. Therefore, elements that are in control will have a small standard deviation with respect to the mean. Elements that are out of control will have a large standard deviation with respect to the mean.

To illustrate the effects of variation, a number of normally distributed functions were plotted (Figure 14 on page 78). Each distribution had the same mean ($\mu = 10$). However, different standard deviations were selected. As shown in the figure, as the standard deviation gets smaller, the probability that an outcome will be at or near the mean increases.

The average time and standard deviation were calculated for a number of setup elements in the race grinding cell (see Table 22 on page 77.) Initially, setup operators were asked to identify which tasks were difficult to control. As shown in the table, the elements which were believed to be out of control had the largest standard deviation with respect to the mean. A rough measure was established to identify elements with excessive variation. It was decided that if the ratio of the standard deviation divided by the mean exceeded 0.4, the process could be considered to be out of control. Otherwise, the process could be considered controllable.

Table 22. Setup Time Variability Measures

Setup Element	Average Time * (μ)	Standard Deviation (s)	s / μ	Predicted To be Uncontrollable
Complete paperwork, get parts & tooling	12	6.84	0.570	
Remove old tooling	5	2.23	0.446	
Set the dresser and workhead	12	9.13	0.761	X
Install new tooling	30	4.35	0.145	
Center grinding wheel to part	5	3.31	0.662	X
Align diamond dresser to grinding wheel	8	3.57	0.447	
Dress off new wheel	8	4.21	0.525	
Find size and location	12	3.50	0.290	
Install loaders	10	16.12	1.612	X
Grind part within tolerances	20	12.87	0.645	X
Return old gages, tooling and lot	10	1.51	0.151	
Send out burn inspection check	5	14.38	2.876	X
Grind 25 parts and clean area	8	0.77	0.096	
Check in	10	1.48	0.148	

All measurements are in minutes.

* The mean time was previously calculated and approved by engineers and setup operators.

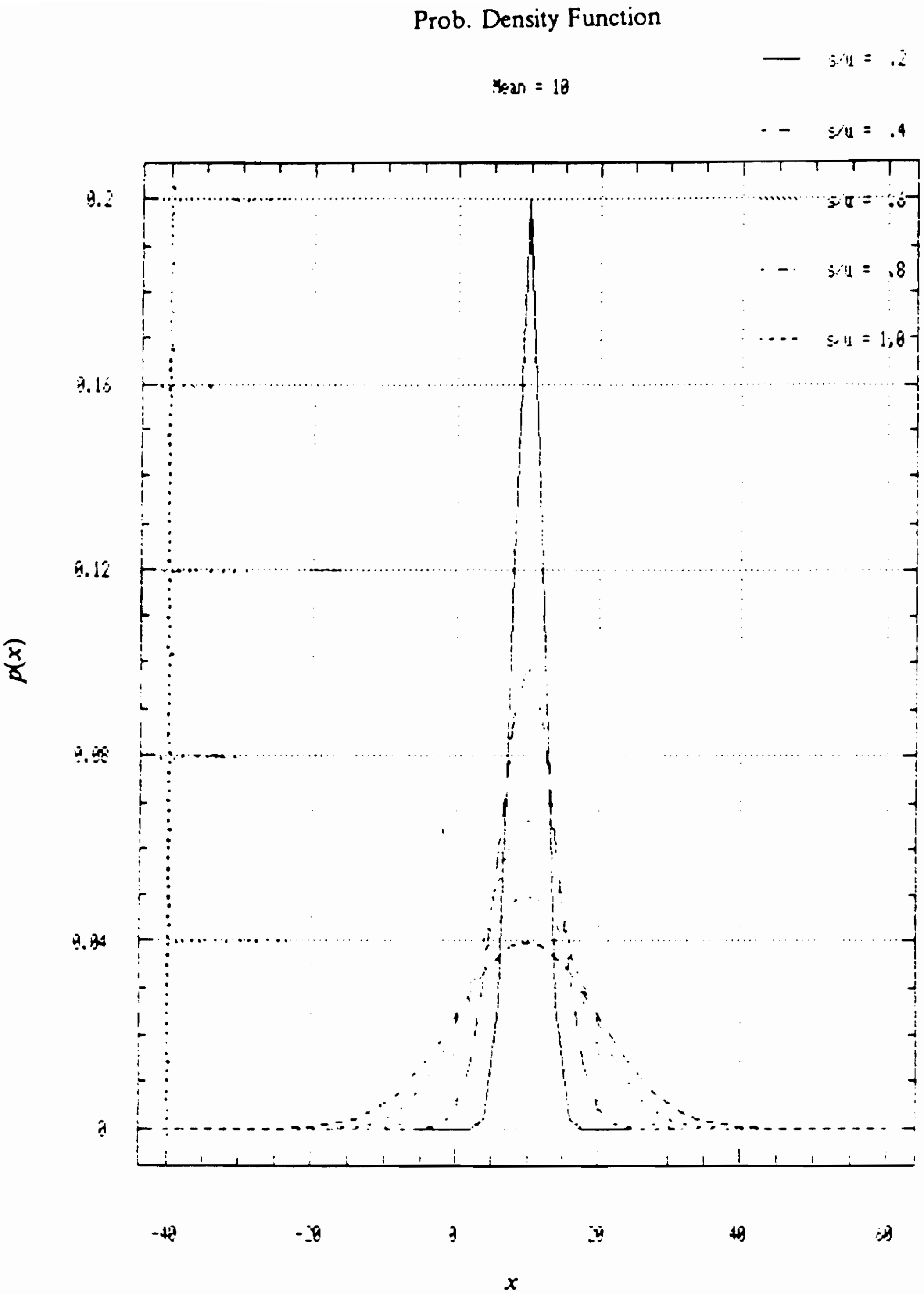


Figure 14. Effects of Variation with Respect to a Constant Mean

Company records were reviewed to determine the causes of setup time variation. Also, it was desired to determine if internal or external elements were primarily responsible. The company that participated in the case study has a computerized data collection system. Computer terminals are located throughout the plant floor. When an employee changes a lot or job assignments (setup or production) or waits for a good or service, he enters this information into the terminal. Reports which summarize this information are generated on a daily, weekly, monthly, quarterly or yearly basis.

Employees are required to log the starting and stopping times for production, setups, waiting for services and waiting for machine adjustments (this includes both the wait and repair time). When production or a setup begins or ends, the employee immediately logs this time into the computer. However, before recording any wait or repair time, the problem must last 15 minutes. If the problem is less than 15 minutes, it is not included in the reports. Because of this rule, some problems are not recorded. Therefore, specific conclusions could not be made since the data is incomplete.

The company reports use four categories to summarize machine activity: standard production, setup, machine adjustment and waiting for goods and services. Company records covering a five week period were analyzed. The results of the study are presented in Table 23.

Table 23. Machine Activity

	Bore Grinding Cell				Race Grinding Cell			
Week	Production	Setup	Machine Adjust.	Wait	Production	Setup	Machine Adjust.	Wait
1	20.8	26.7	4.0	2.1	36.1	90.8	36.3	11.2
2	39.3	39.2	11.1	2.0	84.8	63.0	25.6	5.5
3	46.3	33.4	11.5	---	70.8	65.2	17.3	3.4
4	18.9	20.0	25.3	5.6	67.5	67.5	30.5	9.3
5	28.7	35.0	14.3	0.9	60.9	73.6	27.4	11.2
Mean	30.8	30.9	10.1	1.0	64.0	72.0	27.4	8.1
% of Total	42.3	42.4	13.9	1.4	37.3	42.0	16.0	4.7

The collected data covered over a one month period. The data set is in hours and is a includes all machines in the work cells. In the inner ring bore grinding cell, there are three machines. In the outer ring race grinding cell, there are five machines. The data collected in the study did not include any authorized idle time. For example, if an operator was absent, the lost hours were not recorded.

In both the bore and race grinding machine cells, the amount of time spent manufacturing parts and completing setups was nearly equal. It appeared that more time was spent adjusting the machine than waiting for other services. Unfortunately, the company records did not state if the wait or machine adjustment time was spent during a setup or during production. Also, the causes of the delays were not identified.

A second study was conducted to further understand the causes and effects of setup delays. During a one month period, operators in both areas were asked to document all problems that they encountered during each setup. Specifically, the operators recorded what problems occurred, when they were noticed, and when they were corrected. Some operators participated in the study more actively than others. However, the sample size was large enough ($n > 50$) to draw some general conclusions.

The results of the study are presented in Table 24 on page 81. The results indicate that time spent repairing tooling and/or machinery and waiting for goods and services was roughly equal. Together, these delays accounted for 10 to 15 percent of the total setup time.

With the exception of some machine delays (which occurred while completing an internal element) each type of problem in the study was not directly controlled by the setup operator. Instead, these tasks were completed by machine repairmen, tool crib attendants, gage setters or other service department personnel. These types of tasks were off-site elements which could be completed while a machine is running.

Table 24. Setup Delay Analysis - Bore and Race Grinding Cells

	AREA			
DELAY ELEMENT	I.R. BORE GRINDING CELL		O.R. RACE GRINDING CELL	
	Lost Hours	% of Lost Hours	Lost Hours	% of Lost Hours
Machine	4.74	23.0	31.49	38.2
Tooling	4.66	22.7	10.50	12.7
Pulley Change	----	----	15.64	19.0
Quill Change	1.82	8.8	2.13	2.6
Wait: Gages	6.20	30.2	19.03	23.1
Wait: Elec.	2.00	9.7	3.50	4.2
Other	1.17	5.6	0.18	0.2
Σ Lost Hours	20.59		82.47	

	BORE	RACE	TOTAL
# of Machines	2	5	7
Σ Lost Hours	20.59	82.47	103.06
Σ Setup Hours	189.90	530.60	720.50
Σ Lost /Σ Setup	0.108	0.155	0.143

A study was initiated to determine why such problems were occurring. Specifically, the study was conducted in the tool crib and at a part inspection area. Table 25 on page 83 outlines the causes and effects of various problems. After analyzing this information, it was found that the service department capacities, policies or methods could not meet the demands placed on it. As a result, delays occurred.

The average lot size for the company participating as a case study dropped by 70% over the past 11 years. Also, the number of lots manufactured per year increased by 55%. As a result, the number of setups per year and the demands placed on service departments have increased. Because the capacities and policies, which were established when lot sizes were large, had not been changed to reflect the current demands, delays regularly occurred.

When setups were directly documented in the bore and race grinding areas, other types of delays were encountered that the other studies did not record. These delays were all labor related and contributed to the overall variation. Some setup operators had more experience at machine changeovers than other operators. The average setup time for an experienced operator was less than an inexperienced operator. This was most noticeable when a problem occurred. Usually, an experienced operator can identify and correct a problem faster than a new employee. For example, it was once observed during a setup on a bore grinding machine that the driver could not be properly installed. After a less experienced operator tried for an hour to correct the problem, he called over the area lead-man. The lead-man was able to install the driver within five minutes.

A second type of labor related problem occurred when a changeover could not be completed in a shift. At the beginning of the following shift, a number of setup tasks were observed to be repeated. The amount of repetition varied from setup to setup. When the operators were asked why they were repeating some tasks, they responded that they either did not trust the other setup operator or they did not know what tasks were performed.

Table 25. Problem Causes and Effects

TOOL CRIB	
CAUSE	EFFECTS
• Orders not placed for the start of shift 1	• Heavy work load at the start of shift 1 • Delays at the start of shift 1
• Crib is not notified if an order is cancelled	• Kit sits idle • Tooling cannot be used elsewhere • Other setups may be delayed.
• Unrealistic order / pickup times given	• Kits are not ready • Kits sit idle
PART INSPECTION	
CAUSE	EFFECTS
• Parts are misplaced/mislabeled	• Delays occur
• Inspection equipment operates over capacity	• Part queues increase • Delays occur

A study was performed to determine if the average setup time in the bore and race grinding cells increased if it could not be completed in one shift. A set of data was collected from company records after Phase 1 of the SMED reduction method was implemented. The results of the study are presented in Table 26 on page 84.

The average time and standard deviation are in hours. In both areas, machine setups that took over ten hours to complete were not included in the data set. For these setups, other problems, such as machine or tooling failures, occurred. The results of the study show that there was an approximate 40 percent increase in setup time if it could not be completed in one shift. This increase is due to the time spent repeating setup tasks or identifying what tasks were already completed.

Table 26. Single vs. Double Shift Setups - Bore & Race Grinders

	Bore Grinding Cell		Race Grinding Cell	
	Single Shift	Double Shift	Single Shift	Double Shift
Average	5.2	7.2	4.8	6.8
Std Deviation	0.98	1.43	1.36	1.80
Increase from a Single to a Double Shift Setup		2.0 hours		2.0 hours
% Increase		38%		41%
Frequency of Double Shift Setups		37%		17%

After completing all three studies, it was shown that a number of problems existed which increased the variation in setup time. These types of problems were grouped into three categories; machine/tooling failures, off-site element delays and labor related delays. Most machining and labor related delays affected internal elements, such as getting a part in size. The off-site element delays affected mostly external elements. If the off-site elements delays were significant, setups were prolonged.

Each type of delay which contributes to setup time variation was not unique to a cell. Off-site element delays occur in any cell throughout the entire manufacturing facility. Delays in inspecting parts or retrieving gaging may significantly affect high precision machine cells since the machine tolerances in these areas may be more critical and require more inspection than other areas. Labor related delays can also occur in any type of cell. However, because setups may be more tedious or critical in a high precision machine cell, these delays may impact the variation in setup time more than other areas. Finally, machine related problems can occur in any type of cell or for any type of operation.

4.3 Conclusions

Current setup reduction methods, such as SMED, reduce machine changeover time in high precision machine cells. The reduction in setup time is dependent on the efficiency of the original changeover process, the condition of the machinery and equipment and the motivation to implement an idea. An inefficient setup method poses a greater potential for reduction in setup time than an efficient method. Also, the setup time for a machine which was designed to have greater flexibility (interchangeable parts and subassemblies) can be lowered more than a machine with little flexibility. Finally, if there is little motivation to implement a reduction project, the reduction in setup time will be affected.

Although the current reduction methods lower machine down time, they do not completely correct every setup problem encountered in a high precision machine cell. Three reoccurring types of problems were identified; machine/tooling, off-site elements and labor problems. With the exception of some very specific machine problems, each problem type was not unique to only high precision machine cells (HPMC). Tooling flaws and labor problems can occur at any machine. Also, off-site element problems will affect a number of machining centers. Although these problems are not unique to a HPMC, their effects may be magnified in this type of cell. A high precision operation may have tighter machine tolerances, require more part inspection or remove a smaller amount of stock than other operations. As a result, a HPMC may be more sensitive to machine/tooling, off-site element and labor problems.

Machinery/tooling problems are equipment breakdowns or failures. SMED does correct some of these problems. However, because equipment will eventually fail, such problems will continue to occur. The other two problems, labor and off-site elements, are often not completely addressed by SMED. Labor related problems are training deficiencies and inefficient work habits. One such problem is the time spent by an operator repeating a completed task. Off-site elements are those tasks completed away from the work area. These elements are usually completed by service departments. It has been found that the demands placed on these departments have increased as the average lot size has dropped and the average number of setups per year has increased. If the capacities, policies and methods in these departments do not meet the current demands, delays and other problems occur.

It is generally accepted that there are three components in any system, manpower, materials and a method. SMED focuses primarily on the materials and the methods used in a high precision machine cell. As a result, manpower and off-site element problems in a high precision machine cell are not fully addressed. If these problems are significant, the benefits of reducing setup time by implementing an existing reduction method in a HPMC will be less than anticipated.

Chapter 5

Proposed Setup Reduction Method

5.0 Overview

A method to reduce setup time was developed. The new method incorporates the basic principles of the Single Minute Exchange of Dies method and other methods. The developed method addresses problems that other techniques fail to consider fully such as waiting for goods or services and an inefficient use of labor resources.

The developed method consists of five steps: (1) document the current procedure, (2) simplify the current procedure while using the same equipment and operational policies, (3) identify the opportunities to reduce changeover time by modifying the setup procedure, simplifying/improving setup materials, simplifying off-site elements and making better use of labor resources, (4) prioritize the setup reduction opportunities and (5) implement the projects to reduce changeover time. Both the methodology and the prioritization routine are explained in Section 5.1.

The developed method was applied and evaluated in a high precision machine cell. It was desired to measure the reduction in setup time, particularly the percent reduction which resulted from simplifying off-site elements and improving labor resources. Off-site elements and labor resources are two types of setup problems that other methods fail to completely address. The results of the study are presented in Section 5.2.

5.1 Proposed Setup Reduction Method

It is generally accepted that a system in a manufacturing environment consists of three components, manpower, materials and a method. To successfully reduce setup time, all three components must be addressed. Otherwise, the resulting benefits of the setup reduction efforts may be less than expected. The developed setup reduction procedure focuses on all three components. The procedure is outlined on Table 27.

Table 27. Proposed Setup Reduction Procedure

1.	Document Current Setup Procedure
2.	Simplify the Current Setup Procedure
3.	Identify Opportunities to Reduce Setup Time
	a. Modify the Setup Procedure
	b. Improve/Simplify Setup Materials
	c. Simplify Off-Site Elements
	d. Improve Labor Utilization
4.	Prioritize the Setup Reduction Opportunities
5.	Implement the Projects to Reduce Changeover Time

The first step in the new methodology is to define the current setup procedure. Second, the current procedure is simplified by completing some tasks while the machine is running. Third, opportunities to reduce setup time are identified. These opportunities include modifying equipment so that it can be set in advance, improving the condition and the use of setup materials (tooling and machinery), identifying and correcting problems caused by external sources (waiting for goods or services), and making better use of labor resources.

The fourth step in the new methodology is to prioritize the setup reduction opportunities which require the assistance of other individuals, require capital or affect other areas. The objective of the prioritization routine is to identify those projects which are more beneficial than others with respect to a set of company objectives. The final step is to begin implementing the most beneficial projects.

Steps 1, 2, 3a and 3b of the methodology are based on the Single Minute Exchange of Dies (SMED) method of setup reduction. SMED has been proven to reduce setup time. However, as stated in Chapter 4, the stated reduction claims are not always obtained. In general, SMED reduces setup time by primarily simplifying and improving the setup materials and the methods used at the work area.

Steps 3c and 3d identify those problems that SMED fails to fully address. Step 3c focuses on tasks that are not completed at the work area. Such tasks include building tool kits, preparing gages and completing special inspection tests. Step 3d addresses the use of labor during a machine changeover. Besides identifying how many operators should changeover a machine (a principle of SMED), Step 3d identifies how setup documentation can reduce machine changeover time.

Step 4 is to prioritize the opportunities to reduce machine setup time. If the implementation of a project requires the assistance of other individuals (such as a machine modification), requires capital, or affects other individuals or areas (such as changing a policy to order tooling), the project should be prioritized. The purpose of Step 4 is to identify those setup reduction opportunities that are more beneficial than others with respect to a set of company objectives. Such objectives can include minimizing costs, reducing down time, and improving quality. After prioritizing the opportunities, the most beneficial projects should be implemented, (Step 5). Each step in the new setup reduction method is briefly explained in Section 5.1.1 - 5.1.5. A more detailed explanation is presented in Appendix B.

5.1.1 Step 1: Define the Current Setup Procedure

In order to improve the changeover process, the current method must be fully understood. Specifically, each step in the setup process needs to be defined. There are three steps to define the current setup procedure. First, each setup element or task is identified. All machine changeover elements must be included in the reduction study. Besides direct machine related tasks, such as installing tooling, all lot removal, setup and production preparation tasks must also be included. A false measurement of the total setup time will result if these tasks are omitted.

Second, after defining the setup elements, several setups are documented. Setups can be directly observed or videotaped. The length and frequency of each element should be recorded. Also, any problem, delay and/or solution method should be documented. The final step is to calculate a base time and the standard deviation for each element. The ratio of the standard deviation over the mean should also be calculated to show which tasks appear to be less controllable than others. The standard time is the expected completion time assuming that no major problems occur. This time should include allowances for operator fatigue and personal time. These numbers should be reviewed by setup operators or area supervisors to ensure that the numbers are valid. After completing this step, each setup element's length, deviation and sequence is known.

5.1.2 Step 2: Simplify the Current Setup Procedure

In the past, when lot sizes were large, machine changeover processes were rarely studied. It was believed that the benefits of reducing setup time would not be significant. As a result, inefficient setup processes were allowed to exist. When the average lot size dropped, these problems became more noticeable. Examples of such problems are unnecessary wait time and an unstructured order of operations.

For any machine, a number of machine changeover methods exist. It is not uncommon to observe different procedures to prepare a machine for the same part. If two different processes are compared, the same number of tasks would be observed. However, the total setup time for each method may vary. The reason for this difference is some processes are more efficient than others. Therefore, if the setup procedure was altered so that it became more efficient, the total machine down time would be reduced.

There are two phases in redefining the current setup process, separate internal and external elements and minimize any idle time which is directly controlled by the setup operator. Internal elements are tasks which must be done while a machine is stopped. External elements are those tasks which can be done while a machine is running. Initially, it is not uncommon to observe tasks, which could be completed while a machine is operating, performed while it is stopped. At this point, only those tasks which can be done while a machine is running with the current setup materials should be labelled external. Step 3, modifying the current setup procedure, defines how internal elements can be converted into external elements.

The second phase in redefining the current setup process is to minimize any idle time which can be controlled by the setup operator. There are three steps to complete this phase. First, the order of setup elements must be defined. Tasks which must be completed before others and which are interchangeable should be identified. Second, the tasks which cause idle time are identified. For example, if a part is sent out to be inspected, some waiting occurs. If other tasks were performed during this time, the total machine down time would be reduced. Finally, after determining which tasks can be completed while a machine is running and determining how idle time can be reduced, a new setup procedure is written. A network diagram or other visual tool should be used when developing the new setup procedure. Separate schedules for both internal and external elements should be prepared. Also, it is important that enough time is allotted for the external elements to be completed before production stops. After completing Step 2, an efficient changeover method, which has minimal operator-controlled idle time and has some setup tasks completed in advance, is defined.

5.1.3 Step 3: Identify Setup Reduction Opportunities

Setup time can be reduced by improving or simplifying the changeover methods or the use of materials and labor during the machine changeover. If only one component is addressed, the average setup time may not be fully reduced. A suboptimal changeover method may be created. Therefore, it is important that each component is considered.

Four steps have been defined to identify setup reduction opportunities: modify the setup procedure, improve/simplify setup materials, simplify off-site elements and improve the use of labor. Together, the four steps provide a comprehensive approach to identify setup reduction opportunities. Each step is further explained in Section 5.1.3.a - d.

5.1.3.a. Step 3a: Modifying the Setup Procedure:

The main objective of any setup reduction project is to minimize machine down time. One method to reduce this time is to complete portions of the setup while a machine is still operating. Those tasks which can be completed while a machine manufactures parts are called external elements. Tasks which must be done while a machine is stopped are called internal elements. The purpose of this step is to identify which internal tasks can be converted into external elements.

There are two methods to convert internal elements into external elements, function standardization and duplicate equipment. Function standardization is modifying equipment so that it does not need to be regularly changed or adjusted. Ideas for function standardization may or may not be obvious. It should be regularly asked why each piece of equipment is changed or adjusted. It is from this questioning that ideas for function standardization are generated.

The second approach to convert internal elements into external is to have duplicate tooling or equipment. More tasks may be set in advance if duplicate equipment was available. Any subassembly or operation which is not in direct contact with the machine can be an external element. To determine what additional equipment is necessary, the following questions should be asked about each task:

- What tooling and equipment is used during the task?
- Can additional tooling or equipment become available?
- What modifications to the tooling, equipment or machine are needed so that it can be preset?
- What costs would occur?

If any such idea is implemented, a new setup procedure must be written since the number of internal and external elements will change.

5.1.3.b. Step 3b: Improving/Simplifying Setup Materials:

Setup materials are the tooling, equipment and machinery used in a machine changeover. Setup materials can range from a spindle motor to the clamps used to hold it in place. There are three methods to improve/simplify setup materials: (1) simplify adjustments and clamping procedures, (2) repair broken or faulty equipment (3) perform equipment functional checks prior to starting a setup.

According to various authors, ([Productivity, 1988] and [Hay, 1987]), making machine adjustments accounts for twenty-five percent of the total changeover time. Therefore, machine down time can be reduced if the process of making adjustments is simplified. There are two ways to simplify adjustments: (1) install preset stops and (2) place calibrated markings on the machine. Some items in a machine are designed for a wide range of settings, even if only a small number are needed. If permanent stops are placed on such items, the setup time is shortened as the time spent identifying and setting an object is reduced. If preset stops cannot be used, calibrated markings, such as center lines or a scale, can also reduce setup time by simplifying the adjustment process.

Almost every object in a machine has some type of clamp. One of the most common clamps is a threaded nut and bolt. Although threaded clamps have a strong holding force, they are inefficient to use. More efficient clamps are snaps, pins, single turn clamps and automated clamps. If threaded clamps are replaced with more efficient clamping methods, machine changeover time can be reduced.

Each piece of equipment in a machine will eventually fail. When equipment fails during a setup, delays occur. Therefore, it is important that the materials are in good condition. Otherwise, the average setup time will rise as equipment failures become common. There are two method to prevent equipment from failing during a setup: (1) repair broken or faulty equipment and (2) check the condition of the equipment before starting a setup.

The first method, repairing broken or faulty equipment, not only reduces unproductive machine down time but may also improve product quality and worker safety. When some pieces of equipment break or become worn, a setup operator may not always request the services of machine repair personnel. Instead, the operator may perform a 'quick-fix' by installing cardboard shims or by using alternative equipment. These quick-fix techniques may temporarily correct a problem. However, other negative effects may result. Equipment that needs repair can be identified by documenting setups, reviewing machine down time reports or interviewing setup operators, supervisors or machine repair personnel.

A second method to prevent equipment from failing during a machine changeover is to check its condition before the setup begins. It can be checked by setup operators, tool crib personnel or other employees who can recognize equipment flaws. Although it can be checked at any time, equipment should be inspected after it is removed from the machine. If a flaw is found at this time, more time is available to correct it than if it were found just prior to the starting the setup.

Each method to improve the setup materials, simplifying clamps and adjustments, increasing equipment reliability and inspecting equipment, reduces machine changeover time. Also, improving setup materials can reduce the variability in completing a changeover and increase product quality.

5.1.3.c Step 3c: Simplifying Off-Site Elements:

Another method to reduce setup time is to simplify off-site setup elements. An off-site element is a setup task which is completed away from the work area. Usually, these tasks are not completed by a setup operator. Instead, other personnel or service departments perform these jobs. When a good or service is not readily available, waiting occurs. These delays can account for a significant amount of the total machine down time. Therefore, if the process of completing these elements is simplified and the delays are minimized, machine down time will be reduced.

There are three steps to identify and evaluate which elements should be simplified. First, a list of common delays and problems is prepared. Second, data should be collected to verify these problems. Specifically, the length and frequency of each problem should be documented. Finally, the fundamental causes of each problem are found. This information can be obtained by directly observing the problems, performing a random sample, or interviewing workers and supervisors.

Although each problem has a unique set of causes, some common traits exist. Over the past years, the average number of parts per lot has dropped while the average number of lots run per year has increased. As a result, the number of setups per year have also increased. Therefore, the increase in the number of setups per year has placed more demands on service departments. If the service departments cannot meet these demands, inconsistent service and setup delays occur. These delays can be reduced by improving/simplifying the methods, updating the department policies, and/or increasing the service capacities.

Simplifying off-site elements can reduce the time spent waiting for goods and services. This will not only reduce the average machine down time but also the variation. It should be noted that because a service departments serve the entire production facility, the resulting benefits of improving the turnaround time of a good or service may simultaneously reduce setup time for the entire factory.

5.1.3.d. Step 3d: Improving Labor Utilization:

In most systems, there is some interaction between man and machine. Therefore, if the role of labor is not fully considered in designing or modifying a system, such as a machine setup, problems are inevitable. The purpose of this step is to identify how setup time can be reduced by making better use of labor resources. Specifically, the use of multiple setup operators and the benefits of having documentation available will be discussed.

It is often assumed that only one setup operator should changeover a machine. However, depending on the type of machine, it may be possible to have more than one operator work on the same setup. It has been stated that if multiple operators changeover a machine, machine down time can be reduced as much as 50% [Shingo, 1985].

A Gantt and network chart should be prepared to determine the optimal number of setup operators. The network chart shows which tasks must be performed before others or can be simultaneously completed. The Gantt chart is used to schedule tasks for one or more operators.

A significant amount of training is needed before an operator can efficiently changeover a machine. Operators can receive formal training and/or learn the necessary skills on the job. Some companies have little to no documentation about the changeover procedure. As a result, these companies must rely on their senior operators to orally transfer their knowledge to new employees. If some of this knowledge is lost, operators may have a difficult time completing a setup or correcting a simple problem.

The solution to these problems is to provide documentation about the changeover procedure. Specifically, instructions, a trouble shooting guide and a setup checklist should be given to each operator. If such information is available, the machine changeover time can be reduced.

Setup instructions can help operators learn the correct procedure to changeover a machine. The instructions should be created by engineering and should be reviewed by setup operators. The instruction should contain diagrams and be easy to read. If they are not clearly written, the instructions will not be used.

There are two purposes in creating a trouble shooting guide. First, the guide can help operators quickly identify the cause of a problem. Second, the probability of using the wrong solution to correct a problem can be reduced. The guide must be clearly written and accurate. Specifically, each problem's symptoms, location, cause and solution must be documented. Writing the trouble shooting guide is a continuous process. If it becomes obsolete, it will not be used.

A checklist of setup operations should be given to each operator. Specifically, the list should include the order of operations and the standard completion time. Initially, each operator should record the time when each task is completed. The purpose of recording this information is presented in Table 28 on page 97.

Table 28. Checklist Benefits

- Promotes the use of the standard setup procedure
- Increases operator awareness
- Identifies what tasks are completed
- Identifies operator skill deficiencies
- Collects data for future project justifications

Using the three forms of documentation, the setup checklist, trouble shooting guide, and instructions, can contribute to setup time reduction. The checklist can reduce the probability of repeating a completed task when a setup carries into another shift. The trouble shooting guide can help an operator identify the best solution to correct a problem. Finally, the instructions can be useful as a reference manual if a question arises.

5.1.4 Step 4: Prioritize the Setup Reduction Opportunities

When conducting a setup reduction project, a number of setup reduction opportunities are identified. The benefits of each opportunity vary in both magnitude and frequency. Each setup reduction opportunity may initially appear to warrant implementation. However, constraints exist which may limit the number of projects that can be implemented. Manufacturers may have a limit in the amount of capital or available manpower that can be used to implement a project. Therefore, a method to determine which opportunities will yield the most benefits was developed.

A routine that prioritizes setup reduction opportunities incorporates some of the principles of the Brown Gibson model [Canada and Sullivan, 1989] and the analytic hierarchy process (AHP) [Saaty, 1985]. The prioritization routine consists of four steps: (1) identify relevant criteria, (2) establish preference weights for each criteria, (3) develop a scale for each criteria to evaluate the opportunities, and (4) evaluate and prioritize the setup reduction opportunities. Each step is described in Sections 5.1.4.a - 5.1.4.d, respectively.

The developed prioritization routine can be used in other machine cells. However, both the criteria and the weights should be updated to reflect the objectives of each setup reduction project. If the criteria, scales or weights becomes obsolete, the results of the prioritization routine will be invalid.

5.1.4.a Identifying Relevant Criterion:

Like AHP, the developed prioritization routine decomposes an objective into several attributes. The method uses a hierarchy (see Figure 15 on page 100) to define significant attributes and sub-attributes. The top level of the hierarchy is the main objective. The second level is the general attribute headings. There are two classifications of attributes or criteria, objective and subjective. An objective criteria is one which can be directly measured, such as time. A subjective criteria is one which cannot be easily quantified, such as improving worker safety. Although objective criterion are traditionally used in making justifications, it is important that subjective criteria are included. Otherwise, important benefits may be overlooked.

The third level of the hierarchy includes the relevant criteria that will be used to evaluate setup reduction opportunities. Some relevant objective and subjective criteria are listed in Table 29. Other criteria can be used. However, it is important to include only significant, relevant, independent criteria. If too many measures are used, it will become cumbersome to develop weights and/or evaluate problems.

Table 29. Revelant Criteria - Prioritization Routine

Objective Attributes	Subjective Attributes
• Problem Length	• Worker Safety
• Problem Frequency	• Ergonomics
• Correction Cost	• Product Quality
• Time to Correct the Problem	• Equipment Maintainability

5.1.4.b. Establishing Criteria Weights:

Weights are calculated for each criteria. The larger the value, the more important the criteria is with respect to the overall objectives of the setup reduction project. The prioritization routine uses the pairwise comparison method that Saaty [1985] presents in AHP to calculate criteria weights.

There are six steps to calculate criteria weights. The first step is to prepare a matrix of paired comparisons for both objective and subjective criteria. Key individuals are asked to evaluate each criteria with respect to the others. The proposed scale in Table 30 is used by the individuals to evaluate the attributes. From their responses, a matrix is created (Figure 16 on page 102). The row and column headings are the objective or subjective attributes. Each value in the matrix is the preference ratings of the row attribute compared to a column attribute. All of the values along the diagonal (the preference rating of an attribute compared to itself) must be 1.0. Also, the value of each comparison, x_{ij} must be the inverse of the corresponding comparison, x_{ji}. For example, (see Figure 15), reducing the frequency of a problem is more important than the cost to correct it. A

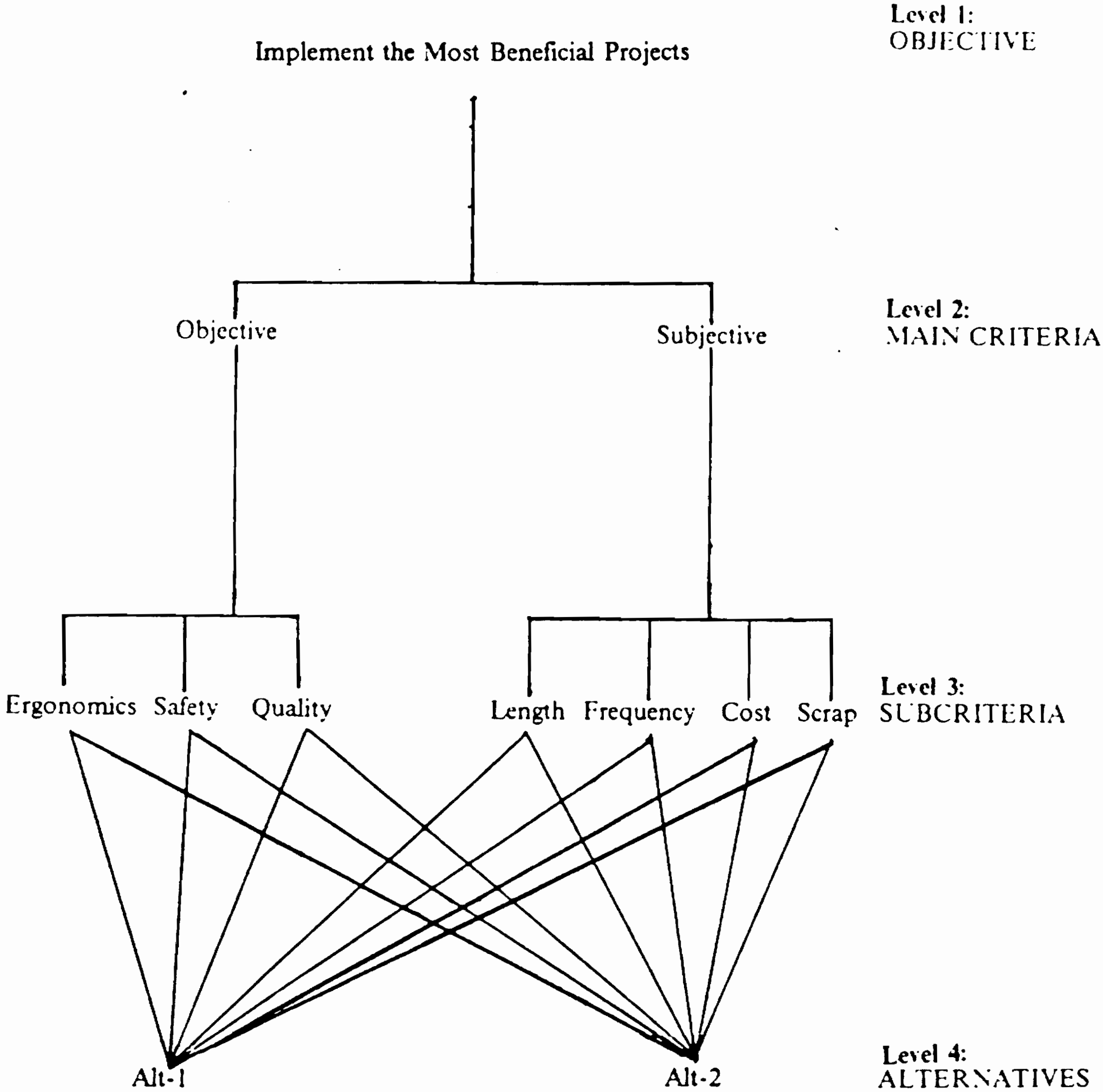


Figure 15. Attribute Criteria Hierarchy

value of 3 is assigned when frequency is compared to the correction cost. Therefore, a value of 1/3 is assigned when the correction cost is compared to the frequency.

Table 30. Preference Comparison Scale - Prioritization Routine

Value	Preference
1	Both attributes are equally preferred
2	Attribute x is preferred over y
4	Attribute x is strongly preferred over y
6	Attribute x is absolutely more important than y

The second step is to normalize the values in each matrix column by dividing each number by the corresponding column sum. When a column is normalized, the sum of its values equals 1.0. The third step is to add the values in each row in the matrix to create a vector (see Figure 16 on page 102). The fourth step is to normalize this vector. The normalized vector is the priority weights for the attributes.

The fifth step is to review the results. Thomas Saaty presents a consistency ratio test to verify the results. The consistency ratio test and an example is presented in Appendix B.

The final step in calculating preference weights is to determine an overall weight of the combined objective and subjective measures. Again, individuals use the same proposed scale presented in Table 30 on page 101 to establish an overall preference. The normalized weights for each measure is found by using formulas 5.1 and 5.2.

$$W_p = \frac{n}{(n + \frac{1}{n})} \qquad [5.1]$$

$$W_w = 1 - W_p \qquad [5.2]$$

where n = Preference value

W_p = Weight for the preferred criteria

W_w = Weight for the weaker criteria

Step 1: Create the initial preference matrices and calculate the sum of each column.

Objective Attributes

	L	F	C
L	1	1/6	1/2
F	6	1	3
C	2	1/3	1
Total	9	1.5	4.5

L = Problem length
F = Problem frequency
C = Anticipated correction cost

Subjective Attributes

	Q	S-E
Q	1	1
S-E	1	1
Total	2	2

Q = Quality
S-E = Safety and Ergonomics

Step 2: Normalize each column so that its sum equals to 1.0.
(Divide each number by its column sum.)

Objective Attributes

	L	F	C
L	0.111	0.111	0.111
F	0.667	0.667	0.667
C	0.222	0.222	0.222

Subjective Attributes

	Q	S-E
Q	0.500	0.500
S-E	0.500	0.500

Step 3: Calculate the matrix eigenvector.
(Add the values of each row)

Objective Attributes

	L	F	C	Vector
L	0.111	0.111	0.111	0.333
F	0.667	0.667	0.667	2.000
C	0.222	0.222	0.222	0.666

Subjective Attributes

	Q	S-E	Vector
Q	0.500	0.500	1.000
S-E	0.500	0.500	1.000

Step 4: Normalize the vector to get the attribute weights.
(Divide each number by the vector sum.)

Objective Attributes

L	0.1111
F	0.6667
C	0.2222

Subjective Attributes

Q	0.5000
S-E	0.5000

Figure 16. Calculating Attribute Weights - Example

For example, assume objective criteria were preferred over subjective criteria by a factor of n = 2. The corresponding weights are:

Objective weight: $W_p = \dfrac{2}{(2 + \frac{1}{2})} = 0.80$

Subjective weight: $W_w = 1 - 0.80 = 0.20$

The resulting numbers are the preference weights. However, before using the weights, they should be reviewed and modified if needed.

5.1.4.c. Developing Criteria Measurement Scales:

For each criteria or attribute, a scale is developed to evaluate each setup reduction opportunity. The numeric values of each scale must be consistent among attributes. Table 31 defines a proposed scale of attribute values. Other values can be used. However, it is important that the scale of value is neither too broad nor too narrow.

Table 31. Criteria Scale - Prioritization Routine

Value	Significance
1	The setup reduction opportunity should not be considered
3	The setup reduction opportunity is worth considering
6	The setup reduction opportunity should be implemented
9	The setup reduction opportunity must be implemented

For the objective measures, discrete numeric ranges are assigned for each scale value. Table 32 presents two hypothetical attributes and the ranges for each value.

Table 32. Hypothetical Objective Measure Scales - Prioritization Routine

Frequency		Cost	
Value	Range	Value	Range
1	Less than 5% of all setups	1	Over $20K
3	Between 5% and 20% of all setups	3	$10K - $20K
6	Between 20% and 50% of all setups	6	Under $10K
9	Over 50% of all setups	9	No cost

Discrete numeric ranges are difficult to develop for subjective measures. Instead, the proposed scale from Table 33 is used to evaluate opportunities. The proposed scale is based on the 1 - 9 scale presented in Table 31 that was used to develop the scale for the objective measures.

Table 33. Subjective Measure Scale - Prioritization Routine

Value	Significance
1	No improvements are possible
3	Indirect or minor improvements are possible
6	Improvements are expected
9	Major improvements are expected

5.1.4.d. Prioritizing Setup Reduction Opportunities:

After establishing the prioritization criteria, weights, and scale, the setup reduction opportunities can be evaluated. Before evaluating any opportunity, a screening process should occur. Some opportunities can be automatically accepted or rejected. In general, an opportunity can be rejected if it violates a functional constraint, such as using a magnetic clamp to hold a computer disk, or requires more resources than is currently available, such as capital. An opportunity can be automatically accepted if it does not require any substantial resources or affect other manufacturing or service areas. For example, distributing checklist or preparing a trouble shooting guide may not require any significant resources and only affects the observed machine area. Therefore, it could be automatically implemented.

The developed prioritization routine uses some of the concepts of the Brown-Gibson model and AHP to evaluate setup reduction opportunities. The principles of the Brown-Gibson model are used to evaluate the opportunities. Each opportunity is evaluated with respect to every objective and subjective attribute. A combined evaluation score is then calculated for each opportunity. The formulas used to calculate a score are based on AHP. The opportunities with the largest scores should be promptly implemented.

There are five steps to calculate an opportunity's score (see Figure 17 on page 106.) First, each opportunity is evaluated with respect to each attribute. A number from the range of attribute values is assigned to each opportunity. The second step is to normalize the evaluation values with respect to each attribute. The third step is to multiply the normalized values by the corresponding attribute weight.

The fourth step is to separately total the weighted objective and subjective attribute values. Again, these numbers are multiplied by their corresponding preference weight. The final step is to add the weighted objective and subjectives values to get the total score.

There are three advantages of using this approach to prioritize opportunities. First, the evaluation process is simple to use and understand. Second, the method allows the user to see the contribution of each objective and subjective attribute in the final score. Third, because the contribution of each attribute is known, the expected results of correcting the problem can be predicted. For example, a short, infrequent problem may have been corrected because it would increase worker safety at no cost. Therefore, worker safety will improve, although the average machine down time will not significantly change.

5.1.5 Step 5: Project Implementation

After prioritizing the proposed setup reduction opportunities, project implementation can begin. The projects with the highest score should be promptly implemented. Projects can be simultaneously implemented. For example, while introducing setup checklists, broken equipment can be repaired and a new tool ordering system can be designed.

One individual or department should be responsible for scheduling and coordinating the implementation of the setup reduction projects. This individual should monitor the progress on each

1. Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES			SUBJECTIVE ATTRIBUTES	
	Length	Frequency	Cost	Quality	Safety/Ergon.
1. Electrical	9	1	1	6	3
2. Find lot	6	3	9	1	1
3. Get tooling	3	3	6	3	1
4. Loader Inst	9	3	1	6	1
5. Part insp.	9	9	1	3	1

2. Normalized Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES			SUBJECTIVE ATTRIBUTES	
	Length	Frequency	Cost	Quality	Safety/Ergon.
1. Electrical	0.2500	0.0576	0.0556	0.3158	0.2500
2. Find lot	0.1667	0.1579	0.5000	0.0526	0.0833
3. Get tooling	0.0833	0.1579	0.3333	0.1579	0.0833
4. Loader Inst	0.2500	0.1579	0.0556	0.3158	0.5000
5. Part insp.	0.2500	0.4737	0.0556	0.1579	0.0833

3. Weighted Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES			SUBJECTIVE ATTRIBUTES	
	Length 0.1111	Frequency 0.6667	Cost 0.2222	Quality 0.5000	Safety/Ergon. 0.5000
1. Electrical	0.0278	0.0351	0.0124	0.1579	0.1250
2. Find lot	0.0185	0.1053	0.1111	0.0263	0.0416
3. Get tooling	0.0092	0.1053	0.0740	0.0790	0.0416
4. Loader Inst	0.0278	0.1053	0.0124	0.1579	0.2500
5. Part insp.	0.0278	0.3158	0.0124	0.0790	0.0416

4. Total Objective & Subjective Measures

PROBLEM	OBJECTIVE ATTRIBUTES	SUBJECTIVE ATTRIBUTES
1. Electrical	0.0753	0.2829
2. Find lot	0.2349	0.0679
3. Get tooling	0.1885	0.1206
4. Loader Inst	0.1455	0.4079
5. Part insp.	0.3560	0.1206

5. Weighted Objective & Subjective Measures and the Total Score

PROBLEM	OBJECTIVE ATTRIBUTES (0.70)	SUBJECTIVE ATTRIBUTES (0.30)	TOTAL SCORE
1. Electrical	0.0527	0.0848	0.1375
2. Find lot	0.1644	0.0204	0.1848
3. Get tooling	0.1319	0.0362	0.1681
4. Loader Inst	0.1018	0.1224	0.2242
5. Part insp.	0.2492	0.0362	0.2854

Figure 17. Example Evaluation Calculations - Prioritization Routine

project. Reports should be regularly prepared and distributed to document the implementation procedure and to maintain motivation to continue the projects.

5.2 Method Validation

The developed setup reduction method was evaluated in another high precision machine cell to determine its effective in reducing setup time. The methodology and the prioritization routine were tested in a raceway honing machine cell. The first step of the new method is to define the current changeover method. The second step and first half of the third step (3a and 3b) incorporate the principles of Single Minute Exchange of Dies method (SMED). Previous tests revealed that a 40% reduction in the setup time was obtained after implementing the projects generated from these steps. The second half of the third step (3c and 3d) identifies opportunities to reduce setup time by simplifying off-site elements and by making better use of labor resources. These types of delays can prolong a machine changeover from 15 to 20 percent. Therefore, it was expected that after implementing the opportunities identified in Steps 3c and 3d, setup time would be reduced by at least 15 percent. In total, the expected reduction in setup time was 55 percent, (40% from the ideas identified from Steps 2, 3a and 3b and 15% from Steps 3c and 3d).

The results of Step 1, documenting the current procedure, are presented in Section 5.2.1. The results of Steps 2, 3a and 3b are presented in Section 5.2.2. The results of Steps 3c and 3d are presented in Section 5.2.3. The development and the results of the prioritization routine is presented in Section 5.2.4. Finally, the implementation of the setup reduction projects and an analysis of the developed methodology is presented in Section 5.2.5.

5.2.1 Step 1: Defining the Current Procedure:

A data set was collected to determine the original average setup time and the standard deviation for the honing machines. The raceway honing cell machines for both inner and outer bearing rings. Although different bearing types are machined, the setup materials and methods are nearly identical. The only difference is the shape of some tooling.

There are four machines in the work cell. Each machine is identical to the others and uses the same tooling. Thirty measurements of both inner ring setup times and outer ring setup times were taken from company records for each machine. The average time and standard deviation is listed in Table 34.

Table 34. Initial Machine Setup Time - Honing Cell

Machine # and Ring Type	Mean	Standard Deviation
22 - Inner ring	4.367	1.762
22 - Outer ring	4.993	3.128
25 - Inner ring	4.987	3.285
25 - Outer ring	4.907	3.467
26 - Inner ring	5.280	4.231
26 - Outer ring	5.520	3.338
31 - Inner ring	5.273	4.923
31 - Outer ring	5.723	5.621

All times are in hours

A difference in means test was used to statistically prove if the data sets were similar enough to be combined. If the data could be pooled together, future studies would be conducted assuming that the collected data for a machine would represent the machine cell as a whole. It was assumed that for each machine, the true standard deviation was unknown, but equal. This assumption was based on the fact that each machine used the same setup procedure, personnel and similar tooling.

For each machine, the inner ring and outer ring setup times could be combined. Also, the data for all outer ring setups could be combined. For the inner ring setup times, the data could be pooled at $\alpha = 0.01$. When $\alpha = 0.05$, all but one combination of machine data could be combined. When all of the data sets are pooled together, the total setup time is 5.13 hours with a standard deviation of 1.94 hours. Figure 18 on page 111 is a histogram of the pooled data. The hypothesis test and formulas used to prove that the data could be combined are presented below. Table 35 on page 110 is a summary of all hypothesis tests.

Additional Notation:

μ_i = Mean setup time for one area

μ_j = Mean setup time for another area

Hypothesis Tests:

$H_0{:}\mu_i - \mu_j = 0$

$H_1{:}\mu_i - \mu_j \neq 0$

$\alpha_1 = 0.01$

$\alpha_2 = 0.05$

Critical Regions:

$t_{(\frac{\alpha_1}{2})} < -2.576$

$t_{(-\frac{\alpha_1}{2})} > 2.576$

$t_{(\frac{\alpha_2}{2})} < -1.960$

$t_{(-\frac{\alpha_2}{2})} > 1.960$

Formulas: See [4.1], [4.2] and [4.3] on page 60

In addition to the setups taken from historical data, ten setups were observed to determine the length, deviation and sequence of each setup element. This level of detail was not available in the historical data. The original changeover method consisted of 23 elements. The initial setup procedure, the standard times and the standard deviation for each element are shown in Table 36 on page 112.

Table 35. Hypothesis Test Summary - Combining Honing Machine Data

Machine Areas	Pooled Variance	Test Statistic (t)	Decision α = 0.01	Decision α = 0.05
22 IR vs. 22 OR	1.564	-1.550	Combine	Combine
25 IR vs. 25 OR	1.837	0.169	Combine	Combine
26 IR vs. 26 OR	1.945	-0.478	Combine	Combine
31 IR vs. 31 OR	2.296	-0.759	Combine	Combine
22 IR vs. 25 IR	1.588	-1.512	Combine	Combine
22 IR vs. 26 IR	1.731	-2.043	Combine	Do not combine
22 IR vs. 31 IR	1.828	-1.919	Combine	Combine
25 IR vs. 26 IR	1.938	-0.585	Combine	Combine
25 IR vs. 31 IR	2.026	-0.547	Combine	Combine
26 IR vs. 31 IR	2.139	0.013	Combine	Combine
22 OR vs. 25 OR	1.816	0.183	Combine	Combine
22 OR vs. 26 OR	1.798	-1.135	Combine	Combine
22 OR vs. 31 OR	2.092	-1.352	Combine	Combine
25 OR vs. 26 OR	1.845	-1.287	Combine	Combine
25 OR vs. 31 OR	2.132	-1.482	Combine	Combine
26 OR vs. 31 OR	2.116	-0.372	Combine	Combine

There are 58 degrees of freedom for all tests.

The average setup time for the observed ten setups was 217 minutes (3.62 hours) with a standard deviation of 31 minutes (0.52 hours). There are two reasons why both the average time and standard deviation were smaller than previously reported in historical records. First, a smaller sample was taken. Second, the setups were directly observed. Because data for the remainder of the validation study would be collected in the same manner, the 3.62 hour average setup time was used as a base time rather than the historical mean of 5.13 hours.

For each element, the ratio of the standard deviation divided by the mean was calculated (see Table 36 on page 112). The higher this ratio, the greater the degree of variability in completing the element. Assuming an arbitrary value of 0.4 as a reasonable cutoff value, 11 out of the 23 elements appeared to be uncontrollable. The findings of this study were later to identify opportunities to reduce setup time.

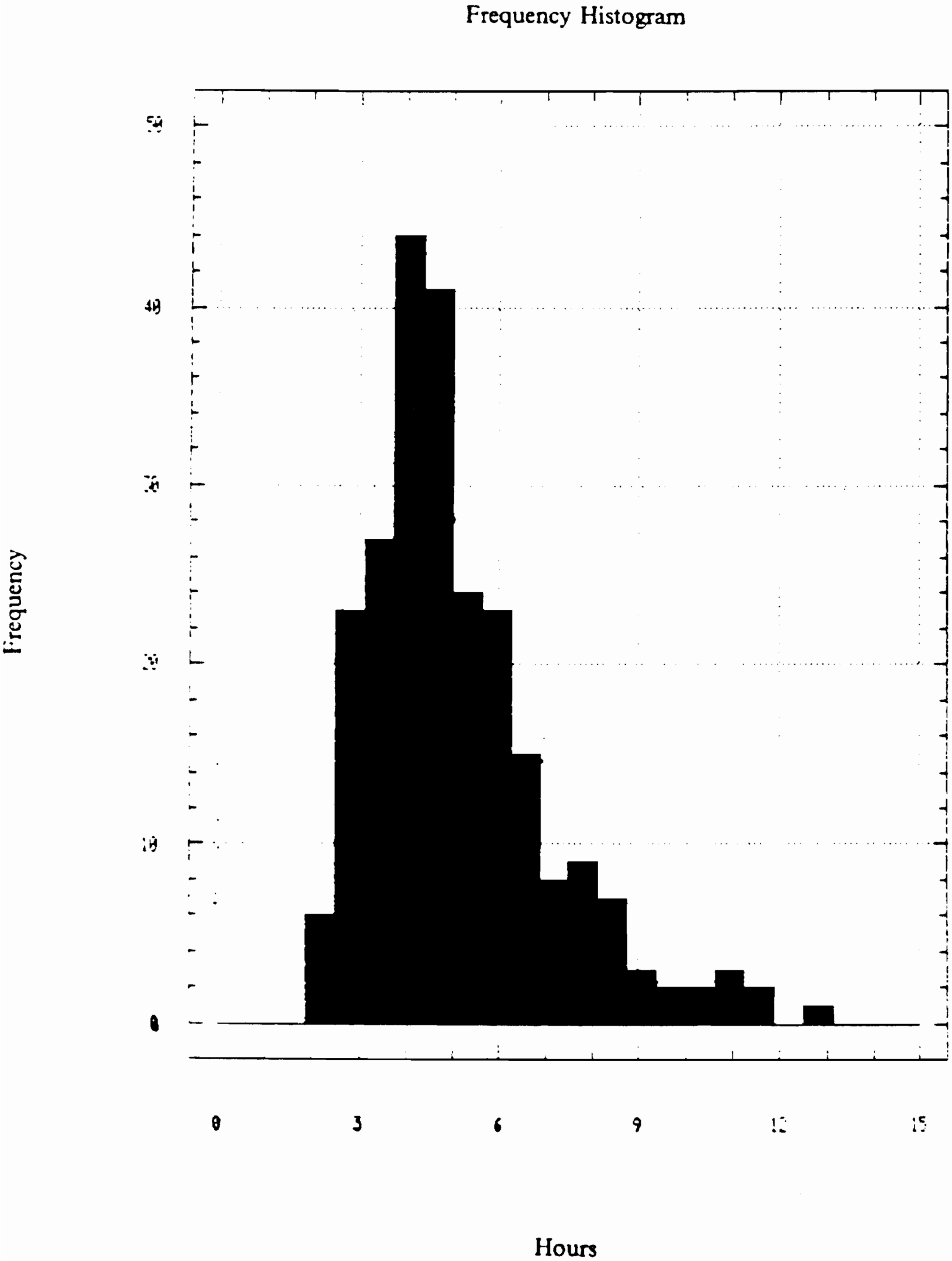


Figure 18. Initial Setup Time Histogram Plot - Developed Method Evaluation

Table 36. Honing Machines - Setup Procedure - Step 1

#	STEP	μ	s	s/μ
0	Complete audit.	25.0	----	-----
1	Count parts. Remove lot and gages. Get new lot, tooling and complete paperwork.	37.0	20.0	0.540
2	Get gaging	4.0	----	-----
3	Remove guards and old tooling	9.1	1.7	0.187
4	Clean & return tooling	6.0	0.8	0.133
5	Install driver, arbor and back pins	5.0	2.6	0.520
6	Install read guide plate. Set radius and location	6.0	2.3	0.383
7	Install carrier plate	3.0	0.8	0.267
8	Bolt front guide plate (FGP) and loading chutes (LC) together	1.0	0.1	0.100
9	Place FGP and LC in machine	3.0	1.5	0.500
10	Put pins into front position slide plate (FPSP) and place FPSP in machine. Install coolant dispersion cap	6.0	3.5	0.583
11	Build stone holder Install stone holder Build loading chute Install loading chute Build exit chute Install exit chute	3.0 3.0 1.0 1.0 1.0 1.0	1.5 2.6 0.2 0.1 0.2 0.2	0.500 0.887 0.200 0.100 0.200 0.200
12	Cut stone	6.0	1.1	0.183
13	Put stone in holder, use optic	10.0	4.0	0.400
14	Build & install pressure plate subassembly Install coolant lines and covers	7.0	5.0	0.714
15	Set spindle speed, oscillation and shape stone	6.0	2.9	0.483
16	Get part in size Pass inspection checks	27.0 38.0	26.4 32.0	0.978 0.842
17	Check-in (by area lead man)	8.0	1.9	0.238

5.2.2 Steps 2, 3a, and 3b:

Steps 2, 3a and 3b of the proposed setup reduction method incorporate the principles of SMED. The second step is to refine the current system while using the same setup materials. This includes identifying and separating internal and external elements and minimizing idle time. It was found that Steps 1, 2, 4, 8, 12, 17 and the subassemblies in Step 11, could be completed while a machine is running (external elements). Also, most of the idle time resulted from goods not being readily available (Steps 1 and 2) and the part inspection test (Step 16).

A network diagram of the setup procedure was prepared, Figure 19 on page 114. Each line in the diagram represents a setup task. Every task is labelled and termed internal or external. If the task is external, the symbol Ext. appears. If the task is internal, the symbol Int. is used. The standard completion time, in minutes, for each task is noted. Each circle or node represents a point in time. Before any task leaving a node can begin, all tasks entering the node must be completed.

The network diagram indicated that the order of completing internal setup tasks could not be altered. However, the order of completing some external setup could be interchanged. For example, gages could be brought to a machine area before or after the required paperwork was completed.

A new setup schedule was written that reduced machine down time. The network diagram was used to ensure that the new schedule did not violate any mechanical or procedural constraints. The new schedule reduced machine down time by completing portions of the setup in advance or while waiting for inspection. Cleaning tooling and the work area could be completed while waiting for inspection. Steps 1, 2, 8, 12 and the subassemblies in Step 11 were to be completed before production ended and during a part audit (Step 0).

The part audit occurs after a lot is honed. This process ensures that the parts have been correctly manufactured before they are sent to be assembled. An audit takes 25 minutes to complete. During the audit, setup operators can complete the external elements.

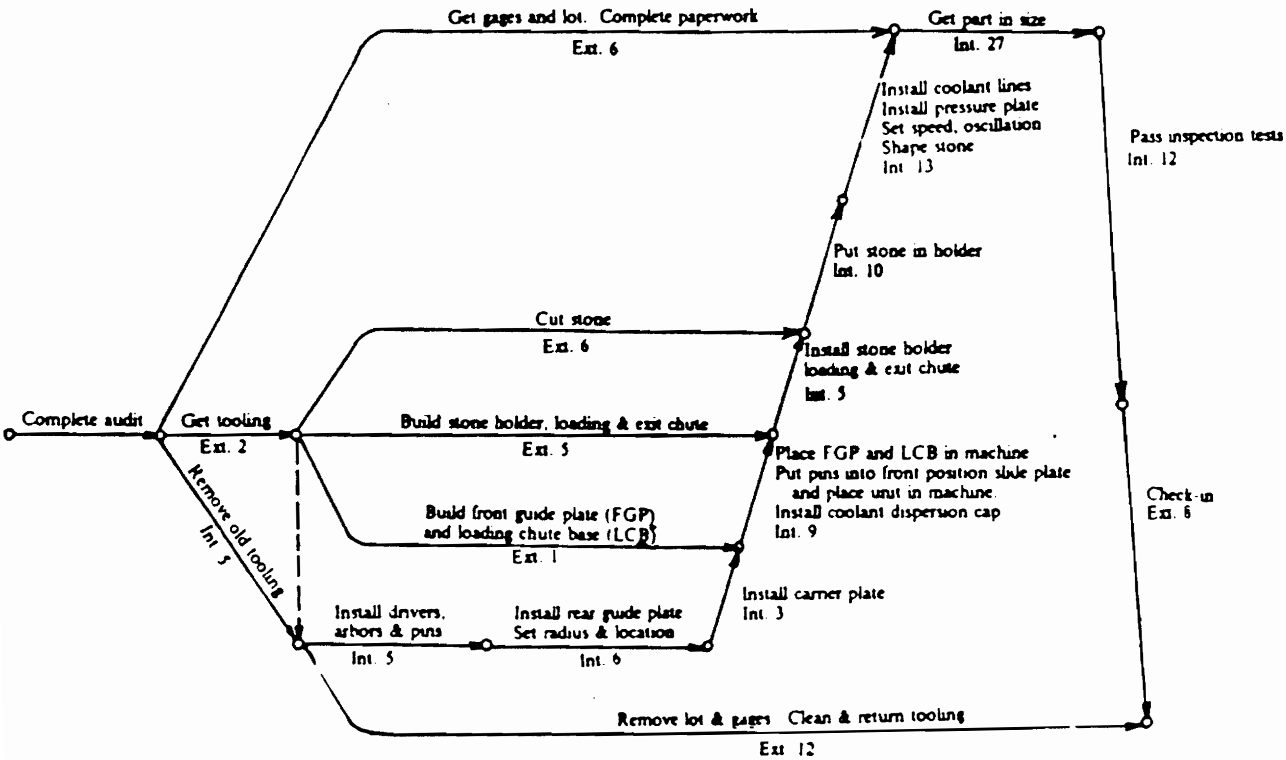


Figure 19. Network Diagram for a Honing Machine Changeover

The honing machines quickly manufacture a lot. The standard production rate in the work cell averages 360 parts per hour. The operator is responsible for monitoring the quality of the parts and loading/unloading the machine. As a result, during production, an operator cannot leave the machine area for a substantial amount of time. Therefore, to minimize machine setup time, the operator would need to complete the paperwork for ordering tooling and gaging during production and retrieve the goods and complete the presets during the part audit.

Step 3a of the setup reduction procedure is to identify opportunities to convert internal elements into external elements. One idea was generated; combine the functions of the back plate, carrier plate and front guide plate. If the items were combined into one unit, the machine down time would be reduced six minutes as Steps 7 and 9 are eliminated. Step 8 (one minute) was not included since it was already an external element.

The proposed idea was found to be infeasible because of design and logistic constraints. A number of units would need to be built for each part outer diameter and width sizes. As a result, the question on where to store the units arises. Also, the units would need to be perfectly flush with both the machine and the part. If any component in a unit breaks, dents or bends, the unit would be unusable. This places additional demands on storing the unit. Currently, the existing system has greater flexiblity by being able to manually adjust the position of any plate and by providing easy storage.

Step 3b is to identify opportunities to improve the setup materials. Some quick release clamps were proposed for the loading/unloading chutes. Because the assembly of these chutes are external elements, the total machine down time was not reduced. Preset stops and calibrated marking were not implemented for three reasons. First, there is not enough room in the machines to place markings or stops on adjustment areas. Second, honing is the last manufacturing operation. Because the operation removes a minute amount of stock and is sensitive to each part dimension, parts within the same family can require different machine settings. Therefore, a large number of preset stops would be needed. Finally, the company that is participating as a case study regularly introduces new part families specified by its customers. As a result, machine flexibility is critical. Preset stops may reduce machine flexibility when compared to the current method.

Two material related problems were identified, electrical switches and a part holding device (drivers). These problems were not directly observed. Instead, they were identified by various setup operators. The electrical switches in the machine would fail and needed to be replaced by machine repairmen. The drivers, which hold a part, need to have a smooth, perpendicular face. If the driver is worn, it cannot properly hold a part. As a result, quality problems occurred and the driver needed to be reground or replaced. The two material related problems were reviewed and prioritized using the proposed routine presented in Section 5.1.2. The results of the study are presented in Section 5.2.4.

5.2.3 Steps 3c and 3d:

The second half of Step 3 presents a procedure to identify setup reduction opportunities which simplify off-site elements (Step 3c) and make better use of labor resources (Step 3d). It was anticipated that after implementing such opportunities, the total machine changeover time would be reduced by an additional 15 percent.

There were a number of off-site elements in the honing cell. These elements included building and retrieving tool kits and gages, locating incoming parts and performing a rate of change inspection test. In total, 110 minutes, or 50.6% of the total setup time, was spent completing these tasks. With the exception of the inspection tests, the off-site elements should be completed while a machine is running. Because there was a significant amount of variation in completing these tasks, setup delays occurred.

Four specific problems, finding a lot, preparing tool kits, building gages and delayed inspection checks, were identified. The magnitude and frequency of each problem varied, (see Table 37). A solution to each problem seemed feasible. Therefore, the prioritization routine was then used to identify which problems should be addressed first. The calculations and results are presented in Section 5.2.4.

Table 37. Off-Site Element Problems - Evaluation

Problem	Length	Frequency
Locating a lot	> 10% of the setup time	Between 5 - 20% of all setups
Retrieve Gages Delays	> 10% of the setup time	Between 5 - 20% of all setups
Retrieve Tooling Delays	Between 1 and 5% of the total setup time	Between 5 - 20% of all setups
Inspection Test Delays	> 10% of the setup time	> 50% of all setups

There were three causes for the off site element delays: (1) communication break downs, (2) the good/service ordering system and (3) overloaded service departments. One problem resulting from a communication breakdown was not being able to locate an incoming lot. Parts entering the honing cell can originate from 4 different areas. If their location is unknown or if parts are misplaced, machine down time increase as operators spend more item searching for the lot. The company that is participating as a case study is also undergoing a major plant layout change. Part storage areas regularly change. If the operators are unfamiliar with the new changes, they may not be able to locate an incoming lot. A second problem resulting from a communication breakdown occurs when an operator forgets to order tooling or gages for an upcoming setup. If the setup begins and orders for tooling or gages have not been placed, delays occur.

The second cause of delays resulted from inefficient or incomplete ordering systems. The methods for ordering tooling and gages were established when lot sizes were larger and when setups were not as frequent. For example, gaging is ordered at the beginning of each machine changeover. The average gage process time is 1.5 hours. Although the initial average setup time for lots in the honing cell was 5.2 hours, partial setups could take 2 hours or less to complete. If gage tooling could not be located, personnel were unavailable or schedule changes occurred, the gages would not be readily available. The final cause of off-site element delays result from overloaded service departments. With smaller lot sizes, more inspection tests (for setup and production) occur. Because the capacities in the inspection areas have not changed, they have become overloaded. As a result, part queues were large and delays occurred.

Step 3d is to make better use of labor resources by determining the optimal number of operators per machine setup and by providing documentation about machine changeovers. Setup schedules, Figure 20 on page 119, were created to determine if machine down time could be reduced by having additional operators changeover a machine. The minimum standard machine setup time for one operator, assuming no problems, would be 107 minutes. If two operators were used, the minimum standard machine down time would remain 107 minutes. There are two reasons why there were no direct benefits of using two setup operators. First, few subassemblies existed. Usually, subassemblies can be simultaneously completed with other tasks. Second, the limited available work space prevented a second operator from assisting another worker.

Setup checklists (Figure 21 on page 120) were written for the honing machines. The lists were distributed to the operators and used for a two week period. During that two week period, the average setup time for those changeovers extending into another shift was reduced from 5.28 hours to 4.98 hours or 5.7%.

5.2.4. Step 4: Prioritization Routine Development and Results:

Six attributes were chosen in agreement with personnel at the company participating as a case study to evaluate setup problems in the honing machine cell. The selected objective attributes were the average problem length, the frequency of the problem, the anticipated correction cost and the predicted time needed to correct the problem. The selected subjective attributes were product quality and worker safety/ergonomics.

Surveys were distributed to key managers. Their responses were analyzed and attribute weights were calculated (Figure 22 on page 122). Objective attributes were preferred over subjective attributes by 10:7. Also, because the company is implementing a new manufacturing strategy to reduce

WORKER 1		
#	STEP	STND. TIME
1A	Count parts. Remove lot & gages. Get lot tooling, paperwork	12
1B	Get gaging	4
2A	Build front guide plate (FGP) and loading chute base (LCB)	1
2B	Build stone holder, loading & exit chute	5
2C	Cut stone	6

WORKER 2		
#	STEP	STND. TIME
	PRODUCTION	
	Complete audit	25
1	Remove guards & old tooling	9
2	Install drivers, pins and arbors	5
3	Install rear guide plate Set radius & location	6
4	Install carrier plate	3
5	Install FGP & LCB	3
6	Put pins into front slide plate & place plate in machine Install coolant cap	6
7	Install stone holder, loader & exit chute	5
8	Put stone in holder, use optic	10
9A	Build & install pressure plate subassembly Install lines & covers	7
9B	Set spindle speed, oscillation & shape stone	6
10A	Get part in size	27
	Pass inspection checks	12
10B	Clean & return tooling	6
11	Check-in	8

Figure 20. Multiple Operator Setup Schedules - Method Evaluation

Part: __________ Oper: ____________ Machine: ____________
Date: __________

Name: _________ Start Time: _______ Start Time: __________
Name: _________ Start Time: _______ Start Time: __________

#	STEP	GOAL TIME	TIME USED	FINISH TASK?
0	Complete audit	25		
1A	Count parts. Remove lot & gages Get lot, tooling & paperwork	12		
1B	Get gaging	4		
2A	Build front guide plate (FGP) and loading chute base (LCB)	1		
2B	Build stone holder, loading chute and exit chute	5		
2C	Cut stone	6		
	END PRODUCTION & AUDIT			
3	Remove guards & old tooling	9		
4	Install drivers, arbors and pins	5		
5	Install rear guide plate. Set radius & location	6		
6	Install carrier plate	3		
7	Place FGP and LC in machine	3		
8	Put pins into front position slide plate and place unit in machine. Install coolant dispersion cap	6		
9	Install stone holder loading & exit chute	5		
10	Put stone in holder, use optic	10		
11A	Build & install pressure plate Install coolant lines and covers	7		
11B	Set spindle speed, oscillation and shape stone	6		
12A	Get part in size Pass inspection checks	27 12		
12B	Clean & return tooling	6		
13	Check-in (by area lead man)	8		
	BEGIN PRODUCTION			

Figure 21. Setup Checklists - Honing Machine Cell

production time and variability, the problem length and frequency were weighted heaviest among the objective attributes. The two subjective attributes, product quality and safety/ergonomics, were equally weighted.

An evaluation scale was created for each attribute according to the procedure outined in Section 5.2. A scale of evaluation values from 1 to 9 was used. If a setup reduction opportunity requires immediate implementation, with respect to the attribute, a value of 9 was assigned. If it does not warrant any attention, a value of 1 was assigned. The evaluation scales for each attribute is defined in Table 38 on page 123.

The resulting attribute weights and evaluation scales were later used to prioritize six setup reduction opportunities. These opportunities consisted of repairing two material/machine problems (drivers and electrical switches) and correcting four off-site element problems (retrieving tooling, retrieving gages, locating an incoming lot and long inspection checks).

Each setup reduction opportunity was evaluated by reviewing historical and collected data, and by discussing the problems with company personnel. The opportunities were prioritized with resect to the criteria scales and the calculated preference weights. The results are summarized in Table 39 on page 124. The calculations are presented in Figure 23 on page 125.

5.2.5 Step 5: Implementation and Evaluation:

The final step of the developed method is to implement the setup reduction opportunities. The amount of time needed to implement a project can vary. Some ideas, such as distributing check-lists, can be immediately implemented. Other ideas, such as redesigning a loading system, may take some time to complete.

It was assumed that the company would implement all the proposed reduction opportunities. Some projects, such as distributing checklists, retrieving tooling in advance and reducing part in-

Step 1: Create the initial preference matrices and calculate the sum of each column.

Objective Attributes

	L	F	C	T
L	1	1/3	2	2
F	3	1	4	4
C	1/2	1/4	1	1
T	1/2	1/4	1	1
Total	5	1.833	8	8

Subjective Attributes

	Q	S-E
Q	1	1
S-E	1	1
Total	2	2

L = Problem length
F = Problem frequency
C = Anticipated correction cost
T = Estimated time to correct the problem

Q = Quality
S-E = Safety and Ergonomics

Step 2: Normalize each column so that its sum equals to 1.0.
(Divide each number by its column sum.)

Objective Attributes

	L	F	C	T
L	0.200	0.182	0.250	0.250
F	0.600	0.545	0.500	0.500
C	0.100	0.136	0.125	0.125
T	0.100	0.136	0.125	0.125

Subjective Attributes

	Q	S-E
Q	0.500	0.500
S-E	0.500	0.500

Step 3: Calculate the matrix eigenvector.
(Add the values of each row)

Objective Attributes

	L	F	C	T	Vector
L	0.200	0.182	0.250	0.250	0.882
F	0.600	0.545	0.500	0.500	2.145
C	0.100	0.136	0.125	0.125	0.486
T	0.100	0.136	0.125	0.125	0.486

Subjective Attributes

	Q	S-E	Vector
Q	0.500	0.500	1.000
S-E	0.500	0.500	1.000

Step 4: Normalize the vector to get the attribute weights.
(Divide each number by the vector sum.)

Objective Attributes

L	0.2206
F	0.5364
C	0.1215
T	0.1215

Subjective Attributes

Q	0.5000
S-E	0.5000

Figure 22. Development of Attribute Weights - Prioritization Routine

Table 38. Attribute Evaluation Scales - Prioritization Routine

OBJECTIVE MEASURES

	Value	Range
Length:	0	$0\% < X \leq 1\%$ of the total setup time
	1	$1\% < X \leq 5\%$
	2	$5\% < X \leq 10\%$
	3	$10\% < X$
Frequency:	0	$0\% < X \leq 5\%$ of all machine changeovers
	1	$5\% < X \leq 20\%$
	2	$20\% < X \leq 50\%$
	3	$50\% < X$
Cost:	0	$X > \$15000$
	1	$\$500 < X \leq \$15000$
	2	$\$0 < X \leq \$500$
	3	$X = \$0$
Time:	0	Over 6 months
	1	Between 1 and 6 months
	2	Between 1 and 4 weeks
	3	Under a week

SUBJECTIVE MEASURES

	Value	Range
All:	0	No improvements
	1	Indirect or minor improvements are possible
	2	Improvements are expected
	3	Major improvements are expected

Table 39. Prioritization Routine Results - Honing Machines

Problem	Type	Score
Part inspection test	Off-site	0.2594
Locate incoming lot	Off-site	0.1656
Electric switches	Machine	0.1551
Retrieve tooling	Off-site	0.1477
Retrieve gaging	Off-site	0.1468
Replace drivers	Machine	0.1256

spection time, were implemented. Other projects, such as reducing the part inspection time, were initiated.

The initial data set was modified to simulate the total machine down time if the opportunities generated from Steps 2, 3a and 3b were implemented and again if the opportunities from Steps 3c and 3d were implemented. The opportunities from Steps 2, 3a and 3b are based on the principles of SMED. The setup reduction opportunities from Steps 3c and 3d address problems that SMED and other methods overlook.

Two different techniques were used to simulate machine setup time. First, if the setup reduction opportunity would eliminate a step or require it to be completed in advance, the completion time of that step was subtracted from the total machine down time. Second, if the reduction opportunity would shorten or simplify a task, the initial completion time was replaced with an expected completion time. Usually, these times were obtained by timing an element without any delays, problems or queues.

The ten documented setups from Step 1 were modified to determine the change in setup time after hypothetically implementing the opportunities generated from Steps 2, 3a and 3b. External elements, (Steps 4, 8, 12, 17 and the subassemblies in Step 11), were subtracted from the total down time. For Steps 1 and 2, only twenty five minutes (the audit time) was subtracted. Therefore, if

1. Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES				SUBJECTIVE ATTRIBUTES	
	Length	Frequency	Cost	Time	Quality	Safety Ergon.
1. Electrical	9	1	1	1	6	3
2. Drivers	9	1	3	1	6	1
3. Find lot	9	3	9	3	1	1
4. Get tooling	3	3	6	3	3	1
5. Get gages	9	3	1	3	3	1
6. Part insp.	9	9	1	3	3	1

2. Normalized Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES				SUBJECTIVE ATTRIBUTES	
	Length	Frequency	Cost	Time	Quality	Safety Ergon.
1. Electrical	0.1875	0.0500	0.0476	0.0714	0.2727	0.3750
2. Drivers	0.1875	0.0500	0.1428	0.0714	0.2727	0.1250
3. Find lot	0.1875	0.1500	0.4286	0.2143	0.0454	0.1250
4. Get tooling	0.0625	0.1500	0.2857	0.2143	0.1364	0.1250
5. Get gages	0.1875	0.1500	0.0476	0.2143	0.1364	0.1250
6. Part insp.	0.1875	0.4500	0.0476	0.2143	0.1364	0.1250

3. Weighted Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES				SUBJECTIVE ATTRIBUTES	
	Length 0.2206	Frequency 0.5364	Cost 0.1215	Time 0.1215	Quality 0.5000	Safety Ergon. 0.5000
1. Electrical	0.0414	0.0268	0.0058	0.0087	0.1364	0.1875
2. Drivers	0.0414	0.0268	0.0178	0.0087	0.1364	0.0625
3. Find lot	0.0414	0.0805	0.0521	0.0260	0.0227	0.0625
4. Get tooling	0.0138	0.0805	0.0347	0.0260	0.0682	0.0625
5. Get gages	0.0414	0.0805	0.0058	0.0260	0.0682	0.0625
6. Part insp.	0.0414	0.2414	0.0058	0.0260	0.0682	0.0625

4. Total Objective & Subjective Measures

PROBLEM	OBJECTIVE ATTRIBUTES	SUBJECTIVE ATTRIBUTES
1. Electrical	0.0827	0.3239
2. Drivers	0.0942	0.1989
3. Find lot	0.2000	0.0852
4. Get tooling	0.1550	0.1307
5. Get gages	0.1537	0.1307
6. Part insp.	0.3146	0.1307

5. Weighted Objective & Subjective Measures and the Total Score

PROBLEM	OBJECTIVE ATTRIBUTES (0.70)	SUBJECTIVE ATTRIBUTES (0.30)	TOTAL SCORE
1. Electrical	0.0579	0.0972	0.1551
2. Drivers	0.0659	0.0597	0.1256
3. Find lot	0.1400	0.0256	0.1656
4. Get tooling	0.1085	0.0392	0.1477
5. Get gages	0.1076	0.0392	0.1468
6. Part insp.	0.2202	0.0392	0.2594

Figure 23. Prioritization Routine Calculations - Honing Machines

more than twenty five minutes were needed, it was assumed that a problem occurred which delayed the setup.

No deduction in the average machine changeover time was made as a result of correcting the electrical switches or drivers. These elements randomly occurred and were never directly observed.

The average setup time after implementing the projects generated from Steps 2, 3a and 3b would be 2.50 hours with a standard deviation of 0.51 hours. This represents a 31% reduction in the total machine down time. To statistically accept or reject the initial 40% reduction claim, a Student T was used. It was assumed that the true standard deviations were unknown and unequal since the changeover process changed. It was found that because the test statistic was within the critical region, the 40% reduction claim was statistically accepted. The hypothesis tests, formulas, calculations and results are presented below:

Notation:

μ_i = Initial average setup time = 3.62 hours

μ_j = Average setup time after completing projects from Steps 2, 3a & 3b = 2.50 hours

s_i = Initial standard deviation = 0.52 hours

s_j = Standard deviation after completing projects from Steps 2, 3a & 3b = 0.51 hours

n_i = Sample size for the initial data set = 10

n_j = Sample size for Steps 2, 3a and 3b = 10

Hypothesis Tests:

$H_0: \mu_i - \mu_j = (.40)3.62 = 1.448$

$H_1: \mu_i - \mu_j \neq 1.448$

Critical Regions at $\alpha = 0.05$

$t < -1.734$ with 18 degrees of freedom

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -1.424 ν = 18.0

Decision: Do not reject H_0

The data set was modified again to determine the machine changeover time if the projects identified from Steps 3c and 3d were implemented. For Step 3c, it was assumed that the four off-site element problems; finding a lot, retrieving tool kits, retrieving gaging and completing inspection checks were corrected. To determine the machine changeover time without such delays, the off-site elements were timed. Elements 1 and 2 (see Table 36 on page 112) could be completed in advance without delaying the start of a setup. Also, without a queue, parts could be inspected and returned within 10 minutes. The data sample was modified to determine the total setup time if the mentioned problems were corrected. Specifically, because it was assumed that Elements 1 and 2 were completed in advance, no machine down time was attributed to these tasks. Also, the observed inspection times, without a queue, were used. No modifications were made for the projects initiated from Step 3d. There were no benefits of having multiple setup operators and the benefits of having documentation were difficult to quantify with respect to the data set.

It was found that the average setup time would be 103 minutes (1.72 hours) with a standard deviation of 25 minutes (0.42 hours). This represents an additional 21.5% reduction in setup time. To statistically accept or reject the proposed 15% reduction claim from the opportunities generated from Steps 3c and 3d, a Student T test was applied. It was assumed that the true standard deviations were unknown and unequal because changes had occurred. After completing the tests, the test statistic was found to be within the critical value limit. Therefore, the proposed 15% reduction claim was statistically accepted. The hypothesis tests, formulas and calculations are presented below:

Notation:

μ_i = Average setup time after implementing projects from Steps 2, 3a & 3b = 2.50 hours

μ_j = Average setup time after implementing projects from Steps 3c & 3d = 1.72 hours

s_i = Standard deviation after implementing projects from Steps 2, 3a & 3b = 0.51 hours

s_j = Standard deviation after implementing projects from Steps 3c & 3d = 0.42 hours

n_i = Sample size for Steps 2, 3a & 3b = 10

n_j = Sample size for Steps 3c & 3d = 10

Hypothesis Tests:

$H_0{:}\mu_i - \mu_j = (.15)3.62 = 0.543$

$H_1{:}\mu_i - \mu_j \neq 0.543$

Critical Regions at $\alpha = 0.05$

$t < -1.738$ with 17.4 degrees of freedom

Formulas: See [4.4] and [4.5] on page 66

Calculations: $t = +1.134$ $\nu = 17.4$

Decision: Do not reject H_0

In total, the proposed setup reduction method could reduce the average machine changeover time by 52.5%. Statistical tests were performed to determine if the initial 55% reduction claim was valid. Again, a Student T test was used. It was assumed that the true standard deviations were unknown and unequal. After completing the tests, it was found that the proposed 55% reduction claim could be statistically accepted. The hypothesis test, formulas and calculations are presented below.

Notation:

μ_i = Average initial setup time = 3.62 hours

μ_j = Average setup time after implementing all projects = 1.72 hours

s_i = Initial standard deviation = 0.52 hours

s_j = Standard deviation after implementing all projects = 0.42 hours

n_i = Sample size for the initial data set = 10

n_j = Sample size for the final data set = 10

Hypothesis Tests:

$H_0{:}\mu_i - \mu_j = (.55)3.62 = 1.991$

$H_1{:}\mu_i - \mu_j \neq 1.991$

Critical Regions at $\alpha = 0.05$

$t < -1.739$ with 17.2 degrees of freedom

Formulas: See [4.4] and [4.5] on page 66

Calculations: t = -0.4305 $\quad$ ν = 17.2

Decision: Do not reject H_0

5.3 Conclusions

A proposed method to reduce setup time in high precision machine cells was developed. The developed setup reduction method consists of five steps. The first step is to document the existing machine changeover method. Each setup element's length, deviation and order is found. Elements with a significant amount of deviation are identified. Step 2 and the first half of Step 3 incorporate three basic principles of Shigeo Shingo's SMED method for setup reduction. Step 2 is to simplify the existing method by converting internal elements into external elements. Also, Step 2 restructures the existing setup procedure so that controllable idle time is avoided. Step 3 is to identify opportunities to reduce machine down time. Step 3 consists of four parts, modifying the existing changeover procedure by converting internal elements into external elements, simplifying improving setup materials, reducing delays caused by off-site elements and making better use of labor resources. Step 4 is to prioritize the setup reduction opportunities. Finally, Step 5 is to implement the reduction projects.

The latter half of Step 3 addresses two issues, the delays caused by off-site elements and the role of labor, that most existing reduction methods do not fully address. The problems resulting from these issues contribute to the overall variation in setup time. By including these two steps, a comprehensive setup reduction method, which addresses manpower, materials and the methodology was written that can be used in high precision cells.

The new setup reduction method also includes a routine to prioritize problems. Previously, problems could be identified, but no formal method to measure their significance existed. The proposed prioritization routine is a modification of the analytical hierarchy process (AHP) and the Brown-Gibson model. The routine evaluates each problem with respect to a number of subjective and objective measures. Each rating is multiplied by their corresponding preference weight and summarized to determine an overall score. The problem with the highest score should be promptly addressed.

The new methodology was tested in another high precision machine cell. A data set was analyzed to determine the reduction in setup time after implementing the projects generated from Steps 2, 3a and 3b, and after Steps 3c and 3d. Initially, the total setup time was 3.62 hours. After implementing the projects generated from Steps 2, 3a and 3b, the total setup time would be 2.50 hours. After implementing the projects generated from Steps 3c and 3d, the total setup time would be 1.72 hours. In total, the machine changeover time could be reduced 52.5% (31% from the projects from Steps 2, 3a and 3b, and 21.5% from Steps 3c and 3d.)

After completing the validation study for the developed method, statistical test were made to validate three claims: (1) a 55% reduction in the total setup time, (2) Steps 2, 3a and 3b contributed a 40% reduction in setup time and (3) Steps 3c and 3d contributed a 15% reduction. Using a difference in means test, each claim was statistically accepted. Therefore, it is concluded that the developed methodology reduces setup time in high precision machine cells. The method is more comprehensive by considering the problems associated with manpower, materials and the methodologies used to changeover a machine. By considering all three components, the methodology was able to reduce setup time in a high precision machine cell further than existing methods, such as SMED.

Chapter 6

Conclusions

6.1 Summary

As manufacturers strive to produce quality goods in a timely manner, the need for rapid, efficient and controllable machine changeovers increases. A number of setup reduction methods exist. These methods can be classified into two groups, frequency-based methods and process-based methods. Frequency-based methods reduce setup time by eliminating or reducing the need to complete portions of the machine changeover. One frequency-based method is to modify tooling or machinery so that multiple operations can be simultaneously completed. Another type of frequency-based method is group technology. Because machine cells have a limited number of operations and use group technology, the benefits of frequency-based methods have already been obtained in a machine cell. Process-based methods reduce setup time by shortening or simplifying the setup procedure. A number of process-based methods exist. Most process-based methods include the basic principles of Shigeo Shingo's method, SMED. Shingo states that setup time can be reduced by completing portions of the machine changeover while it is still running and by simplifying the tasks performed at the machine.

SMED was evaluated in two high precision machine cells. Shingo and others claim that SMED reduces setup time from 70 to 90 percent. The actual resulting reduction in setup time varied between cells. A 42% reduction in setup was obtained in one cell and 67% in another.

There were four reasons for the difference in results. First, SMED was more effective in cells with machines which were already designed for flexible manufacturing and/or had subassemblies and interchangeable equipment. Second, SMED was more beneficial in machine cells which had an inefficient or undefined original setup procedure. Third, the condition of the equipment affected the resulting reduction in changeover time. Finally, if there was not enough motivation to implement SMED, the results would be less than anticipated.

After implementing SMED, some setup problems were not completely corrected. As a result, there was still variability in changeover time. Two separate studies revealed that machine/tooling failures, labor related problems and problems with off-site tasks still occurred. Machine and tooling failures were primarily dependent on their mean time to failure. Implementing SMED will improve some equipment. However, because no piece of equipment has an infinite life, it will eventually need to be repaired or replaced.

The other two types of problems, labor and off-site tasks, are not fully addressed by SMED. Together, these problems accounted for approximately 15 percent of the total machine down time and contributed to variation in setup time.

Labor related problems resulted from ineffective training procedures, operator communication breakdowns and poor management of labor resources. Off-site element problems (tasks completed away from the machine) resulted from goods or services not being readily available. The reason for such delays is due to the gradual changes in the manufacturing environment. Recent trends indicate that the number of setups per year has been increasing. As a result, the demands placed on service departments that complete the off-site elements, have changed. If the capacities, policies and/or methods in the service departments do not meet the current demands, problems and delays occur.

A methodology was developed to reduce setup time. The methodology consisted of five steps. The first step was to document the original changeover process to determine the length, order and standard deviation of each element. Steps 2, 3a and 3b incorporate the principles of Shigeo Shingo's method, SMED. Step 2 reduces machine setup time by completing some setup tasks in advance and by minimizing any controllable down time. The third step identifies opportunities to reduce setup time. There are four parts to Step 3. Step 3a identifies opportunities to modify tooling or machinery so that additional tasks can be completed in advance. Step 3b identifies opportunities to simplify or improve the materials used in a setup by simplifying adjustments, increasing the reliability of equipment and regularly inspecting equipment for flaws or failures.

Step 3c is a procedure to identify significant problems with off-site elements. Step 3d demonstrates how setup time can be reduced by making better use of labor resources. Specifically, the benefits of setup instructions, a trouble shooting guide and checklists are discussed.

The fourth step of the developed method is to prioritize the setup reduction opportunities which may require additional resources and/or affect multiple areas. The prioritization routine is a modification of the Analytical Hierarchy Process (AHP) and the Brown Gibson model. The method uses both objective and subjectives measures. Priority weights are calculated for each measure and used to evaluate and prioritize the setup reduction opportunities. The final step is to implement the prioritized projects.

The developed method was tested in another high precision machine cell. The method reduced the total machine down time 52.5%. The proposed setup reduction projects from Steps 2, 3a and 3b lowered setup time 31%. The proposed projects from steps 3c and 3d reduced setup time 21.5%. The additional 21.5% reduction was gained by addressing the role of labor and the tasks performed away from the work cell. Therefore, the new methodology could reduce setup time in high precision machine cells further than existing methods, such as SMED, by considering the manpower, materials and methods used for tasks completed at and away from the work area.

The evaluation of SMED and the developed setup reduction method were conducted in a high precision machine cell (HPMC). It was found that the encountered problems, such as inspection delays or tooling failures, were not unique to a HPMC. These problems could also occur in a low precision cell. Instead, because a HPMC may require additional inspection or more precise tooling, the effects of these setup problems may be magnified.

The developed setup reduction method incorporates the basic principles of SMED which can be applied to both high and low precision machine cells. Also, the developed method corrects other setup problems by improving/simplifying the use of manpower, the materials and the methods used for tasks completed at and away from the machine. Because this approach to reduce setup time is not exclusive to HPMC, it will be assumed that the developed methodology could be used in any type of machine cell.

The developed methodology should not be exclusively used for machinery not in a cell. It was assumed that cellular manufacturing already obtains the benefits of group technology and other frequency-based methods. Therefore, exclusive use of the developed setup reduction methodology for machinery not in cells may not substantially reduce the average machine changeover time. Frequency-based setup reduction efforts may also be needed.

6.2 Contributions

This research has attempted to make three contributions to the field of setup reduction. First, an evaluation of the Single Minute Exchange of Dies (SMED) method was completed in a high precision machine cell (HPMC). Second, the causes and effects of setup related problems in a HPMC which SMED did not fully correct were identified. Finally, a setup reduction method was developed and validated in another HPMC.

SMED was evaluated in two high precision machine cells. A reduction in setup time was observed in both cells. However, the results varied from cell to cell. The specific percent reduction claims of each phase of SMED were not always obtained. Also, a number of setup related problems were not corrected after implementing SMED.

Four reasons were identified for the varied percent reduction in setup time. First, SMED is more beneficial for machinery that has a number of subassemblies or has been designed for flexibility. Second, the average setup time for procedures which were originally unstructured or inefficient will be reduced further than well structured, efficient procedures. Third, the original condition of equipment will affect the percent reduction in setup time. Finally, the motivation level of a company can impact the overall results of implementing SMED.

Three types of setup problems were identified which were not completely eliminated after implementing SMED. Together, these problems caused variation in the average setup time. The three types of problems were machine/tooling failures, delays from setup elements completed away from the machine and labor related problems. Machine and tooling failures are dependent on their reliability and mean time to failure. Almost all types of equipment will eventually fail. Improvements can be made to increase the mean time to failure. However, at some point, equipment failure or replacement will occur.

The other two types of problems, off-site element delays and labor problems, were not fully addressed by SMED. SMED and perhaps other similar setup reduction methods primarily reduce machine changeover time by simplifying and improving the methods and equipment used at the work area. Specific labor problems and elements completed away from the work area usually do not receive any direct attention. Together, these types of problems increase machine changeover time and contribute to setup time variation.

The causes of these problems vary. However, some general conclusions can be made. Labor related problems result from a lack of communication between employees, a lack of documentation or information, or an inefficient or incomplete training program. Delays from off-site tasks, such as preparing tool kits, usually occur when area capacities or procedures do not meet the current demands. If a company's average lot size drops, the average number of lots per year increase. As a result, the number of setups per year and the demands placed on service departments increase. Because this trend occurs over a period of time, the capacities or procedures can become inefficient or ineffective.

A setup reduction method was developed. The method includes three features that other methods do not. First, the developed method incorporates the principles of SMED and addresses problems that SMED does not fully consider, such as labor or off-site element delays. Second, the new method provides additional instructions on how to collect data and develop a new setup procedure. The third feature of the developed methodology is it includes a procedure to prioritize the proposed projects or opportunities to reduce setup time. Existing machine changeover reduction methods do not have any techniques to determine which setup reduction opportunities are more beneficial with respect to a set of project objectives.

The new method was evaluated in another high precision machine cell. A 52.5% reduction in setup time occurred. The principles of SMED accounted for 31% of the total 52.5% reduction in setup time. The contributions of this research accounted for the remaining 21.5%. The prioritization routine was also applied and clearly indicated which opportunities to reduce setup time were more beneficial than others. The main reason for the success of the developed method was its approach to reduce setup time is more comprehensive than others by considering the role of labor, materials, and the methodology.

The evaluation of the developed setup reduction method and SMED was conducted in high precision machine cells. It was found that the encountered problems, labor, tooling/machine breakdowns and off-site element delays, were not exclusive to a high precision machine cell (HPMC). Low precision cells could also encounter these problems. Instead, because a HPMC may have tighter tolerances, remove a smaller amount of stock, and/or require additional inspection, it may be more sensitive to such problems. Because the problems and solutions methods are not exclusive to a high precision machine cell, it is assumed that the developed methodology can be used in all types of machine cells.

6.3 Future Research

Literature has been recently written by Shingo [1985], Hays [1987] and others about methods to reduce machine changeover time. This research presented in this thesis has identified four other fields of future research. First, the developed methodology could be tested in other manufacturing environments. Second, the prioritization routine could be applied in a number of manufacturing facilities to determine which attributes are universally more significant than others. Third, additional research is needed for justifying design changes for both equipment and machinery. Finally, the benefits of TPM and TQM in reducing setup time could be quantified.

The research was conducted solely in high precision machine cells. Although, the methodology was written to addresses problems in these areas, it may be applicable to machines in low precision cells or even machines not in cells. Additional tests would need to be conducted in different machining environments before any definite conclusions could be reached. By reevaluating the proposed methodology in other areas, other problems and solution methods may be revealed.

The prioritization routine was tested in only one company. Although different individuals provided information to establish criteria and priority weights, questions still remain. Specifically, the number of criteria may or may not be complete. Also, the calculated preference weights may or may not be universal. A simulation model could be developed which determines what criteria are more significant than others. Data could be taken from other companies and analyzed. The simulation model could follow the procedure that Siegel [1987] used to analyze machine scheduling methods.

A number of reduction methods identify opportunities to reduce setup time by modifying equipment so that it can be preset or by implementing quick release clamps. Both methods have been proven to lower machine down time. However, cost justifying these improvements can be difficult. Therefore, a need exists for a clear method to justify tooling or machine design changes.

TPM and TQM, total productive maintenance and total quality management, are two means of improving manufacturing productivity and quality. During this research, machine/tooling failures and long inspection cycle times increased machine changeover time. By implementing a TPM and/or TQM program, it is possible to eliminate some of these problems. A quantified reduction in setup time as a result of implementing TPM and/or TQM is undefined. Also, research could be performed to determine how to integrate a TPM and/or TQM program into a setup reduction methodology.

There is much interest in the field of setup reduction. Because it is relatively new, few methods and techniques exist. This research had four major objectives. First, an existing setup reduction method, SMED, was evaluated to determine its strengths and weaknesses. Second, the causes and effects of problems not corrected by SMED were identified. Third, a setup reduction method was developed which addressed some problems that other methods overlooked. Finally, the developed method was evaluated in another high precision machine cell. The research also showed that there are other areas of setup reduction which could be studied. Because it appears that additional companies will stress the importance of setup reduction, additional research in this field will be beneficial.

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Appendix A

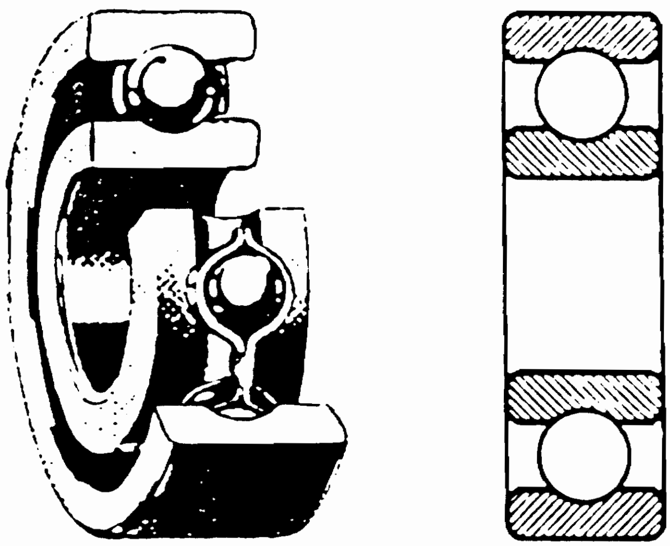
Bearing Nomenclature

The purpose of this appendix is to define fundamental nomenclature of ball bearings. There are two sections in this appendix; parts of a bearing and the characteristics of the bearings that are inspected.

Parts of a Ball Bearing:

Figure 24 on page 143 shows a completed bearing. Most bearings consist of five components; the outer ring, the inner ring, the cage, the bearing balls and the closures.

The outer ring, Figure 25 on page 144, and inner ring, Figure 26 on page 145, holds the metal balls in the bearing. The curved path in the rings, called the raceway, is where the bearing balls ride. The outer diameter of the outer ring is the size of a bearing. The outer diameter is the part of the bearing that is in contact with customer's housing. The inner hole of the inner ring is called the bore. The bore is the part of a bearing that contacts a customer's machine shaft.



This is what a ball bearing would look like if it had a slice cut out of it. The drawing on the right shows a ball bearing that has been cut in half.

Section view of an assembled deep-groove ball bearing

Figure 24. Components of a Bearing

THE OUTER RING

The outer ring of a bearing keeps the balls inside the bearing from flying off into space. The curved part of the outer ring, called the raceway, is where the bearing balls ride. The outer diameter of the outer ring is the part of the bearing that contacts the customer's machine **housing** when the assembled bearings are installed.

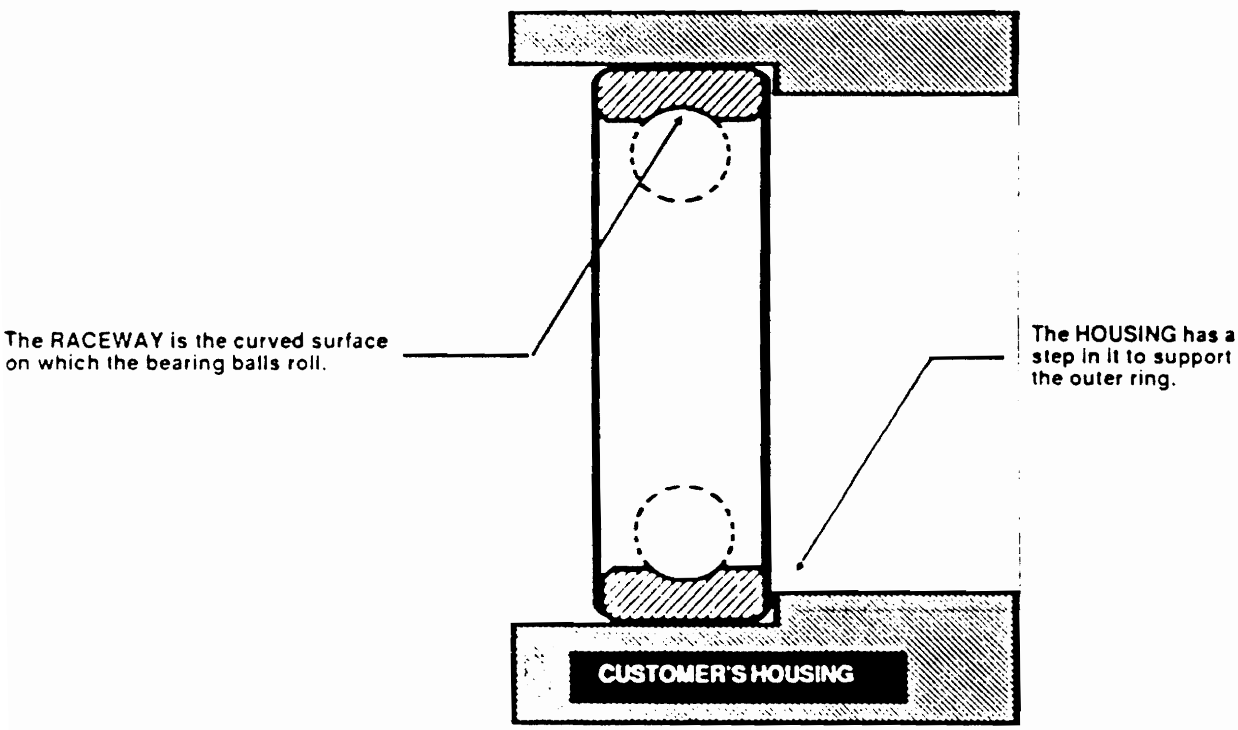


Figure 25. Bearing Outer Ring

THE INNER RING

The bearing inner ring also holds the balls inside the bearing. The curved portion on the outer diameter of the ring, called the **raceway**, is where the bearing balls ride. The hole through the inner ring, called the **bore**, is the part of the bearing that contacts the customer's machine **shaft** when the assembled bearings are installed.

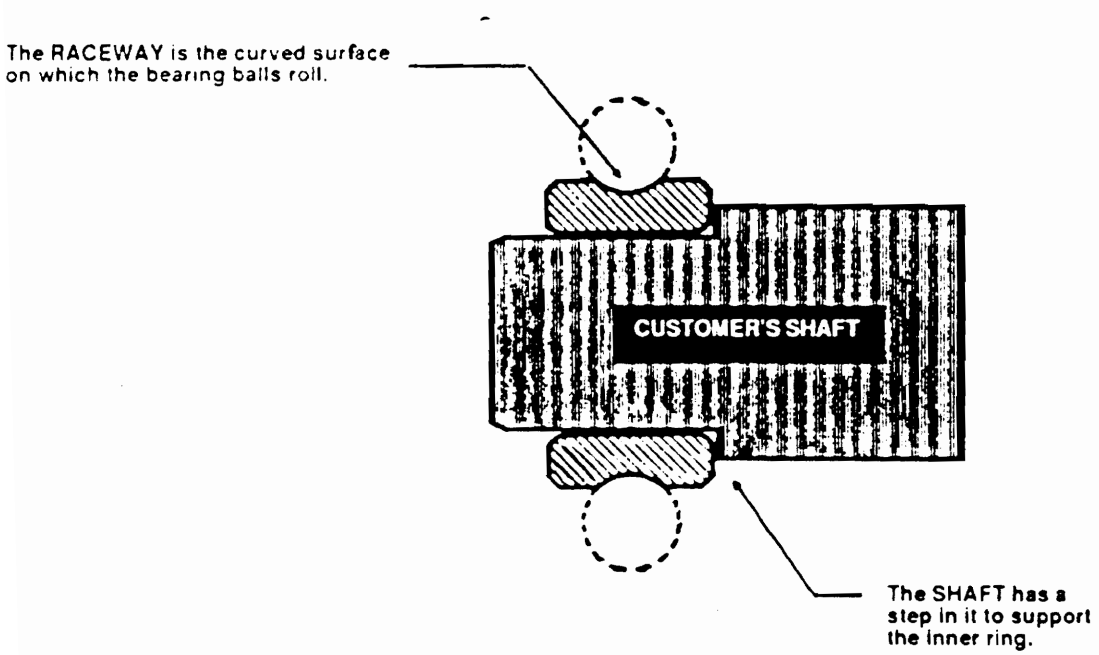


Figure 26. Bearing Inner Ring

The purpose of the cage, Figure 27 on page 147, is to prevent the bearing balls from bumping into each other when the bearing operates. The purpose of the closures, Figure 28 on page 148, is to keep contaminants out of the raceways. There are two types of closures; shields and seals.

Bearing Inspection:

Product quality is important to the Barden Corporation. Bearings are inspected throughout the entire manufacturing process. Before a bearing can be assembled, each component must pass inspection. Bearings are both visually and dimensionally inspection. Besides part width and diameter, inspectors and machine operators measure other part characteristics as shown in Figure 29 on page 149.

THE CAGE

The job of the cage in a ball bearing is to keep the bearing balls from bumping into each other as the bearing rotates. The movement of the cage also helps to spread lubricant around in the bearing as it rotates. Cages made of bronze and other metals are used for high-temperature applications, while plastic cages are used for low-temperature, low-speed requirements.

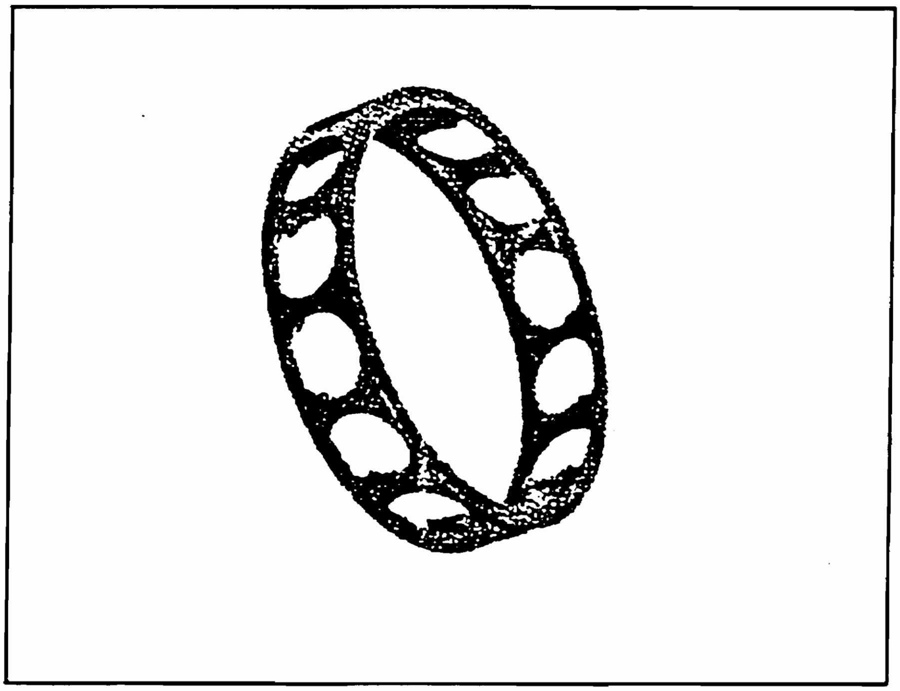


Figure 27. Bearing Cage

CLOSURES

Closures are installed on Barden ball bearings to keep dust, dirt and other contaminants out of the raceway areas of the bearing. Closures are also used to retain the lubricant in greased bearings. The two types of closures used at Barden are **shields** and **seals**. Shields protect the bearing raceway areas, but not as completely as seals do.

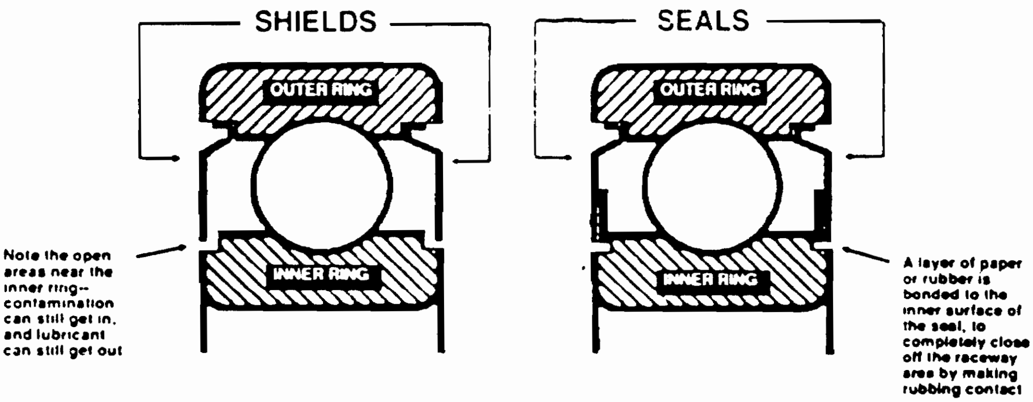


Figure 28. Bearing Closures

INSPECTION (parts)

When inner and outer rings are clean, they are **visually** and **dimensionally** inspected to make sure they still meet Barden's strict requirements. Parts that pass inspection are sent to the **clean rooms** for the first step in the bearing assembly process. Besides part **width** and **diameter,** some of the things inspectors watch for in parts are shown below.

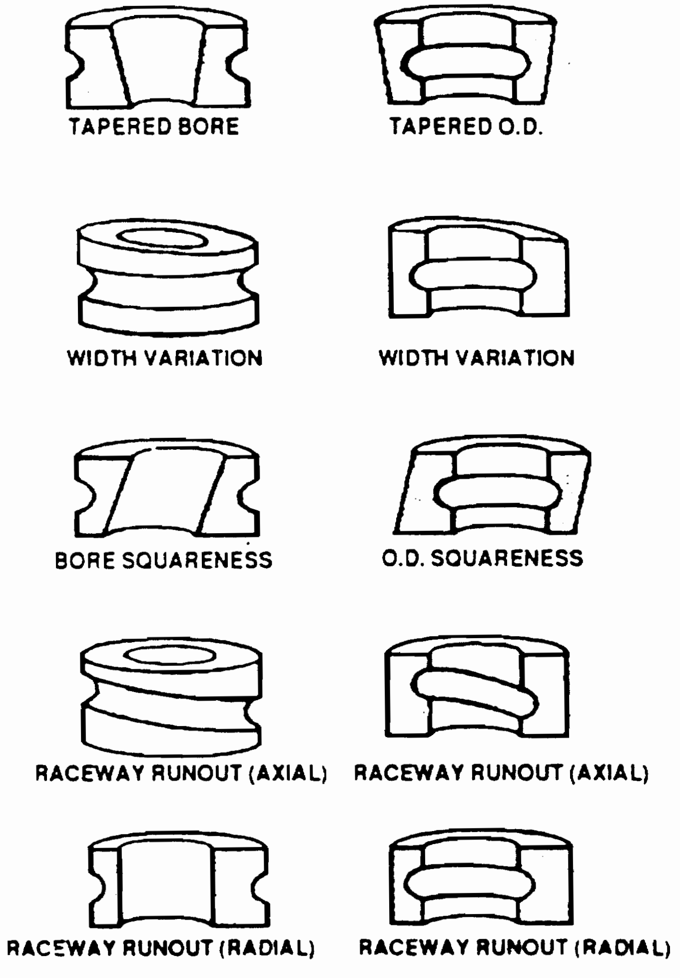


Figure 29. Inspection Nomenclature

Appendix B

Setup Reduction Manual

The purpose of this manual is to present a method to reduce setup time in high precision machine cells (HPMC). The manual presents information concerning the procedure to reduce setup time, the method to collect documention and the routine to prioritize problems.

This method to reduce setup time has three assumptions. First, the observed machinery is assumed to be in a cell. Second, it is assumed that tooling is efficiently used. Finally, the benefits of group technology, such as partial setups, already exist.

The setup reduction procedure has proven to reduce the average machine changeover time in a high precision cell by 55%. The basis of the procedure is to successfully reduce machine setup time, all three machine changeover components, manpower, materials and a method, must be improved and simplified.

The manual consists of five sections. Section 1 defines the procedure to document the current changeover procedure. Section 2 presents instructions to reduce setup time by improving the setup procedure while using the same equipment and operating policies. Section 3 identifies opportunities to reduce setup time by improving or simplifying the setup method, materials and the labor skills. Section 4 presents a procedure to prioritize the setup reduction opportunities. Section 5 presents some guidelines to implement and coordinate the setup reduction projects. Figure 30 on page 152 outlines the recommended procedure to reduce setup time. The figure illustrates when each task should begin, who should be involved and what section presents specific information about the task.

Section 1: Define the Current Setup Procedure

In order to minimize machine setup time, the original method must be understood. Specifically, each step in the setup process must be defined and assigned a base time. This information will later be used to demonstrate the benefits of the setup reduction project and to justify any equipment purchases.

There are three steps to define the current setup process. First, a list of the setup tasks is created. Second, several setups are documented. Finally, a standard or base time is assigned to each setup task. Each step will be explained in Sections 1.1, 1.2 and 1.3 respectively.

1.1 Identifying All Setup Tasks

Purpose: Setup time is defined as the elapsed time between producing the last part of an outgoing lot to the first good part of an incoming lot. During this time, a number of tasks are completed. These tasks are not only replacing and adjusting tooling, but also preparing the work area for production, completing paperwork and performing other tasks. Therefore, the purpose of this step is to identify all relevant setup tasks that are performed. It is assumed that the current process does

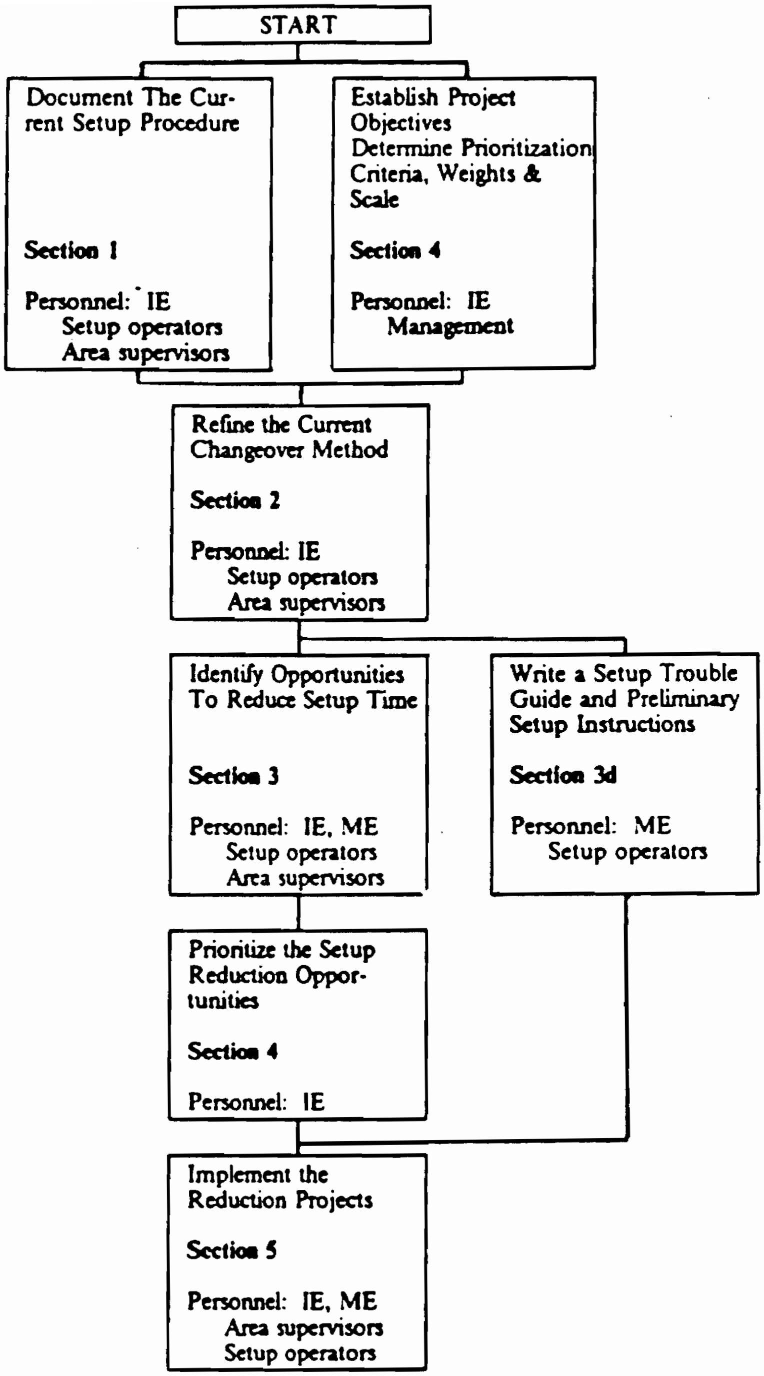


Figure 30. Setup Reduction Schedule

not have any setup tasks performed while the machine is running. If this is not true, these setup operations should also be included.

Personnel Required: An industrial engineer and an experienced setup operator should develop the list of setup tasks.

Procedure: Direct observations and discussions should be used to identify all setup tasks. Although videotaping a setup can be helpful, it has several drawbacks. First, some setup tasks are completed away from the work area. Unless a portable camera is used, these tasks may not be recorded. Second, some machines have a confined working area. As a result, it may be difficult to film some tasks. Third, some setup operators may become camera shy.

The procedure to identify setup tasks is defined in Table 40. The first step is to determine what lot removal tasks are performed. Often, an operator must sign out an outgoing lot before a new one is brought to the area. Other tasks that may need to be performed are counting parts, completing paperwork, removing the lot, returning gages and cleaning the work area. The industrial engineer should either interview a setup operator or directly observe the process to determine what tasks are performed.

Table 40. Identifying Setup Tasks

1. Determine lot removal tasks
2. Determine setup preparation tasks
3. Document each machine changeover step
4. Record all post setup tasks
5. Validate the findings

The second step is to determine what tasks are done to prepare the work area for the next machine changeover. Again, direct observation or discussion can be used. Some common setup preparation tasks are ordering and retrieving tool kits, getting new gages and completing paperwork.

The third step is to document each setup task. It is recommended that the industrial engineer directly observe a complete machine changeover. Besides identifying each setup element, the industrial engineer should also become familiar with the equipment and terminology. Also, the setup operator can answer any questions at this time.

The fourth step is to identify each task which is performed after a good part is manufactured. These tasks can be found through direct observation or discussion. Examples of such tasks are returning any special setup gages or indicators and cleaning the work area.

The final step is to validate the list of elements. At this time, a list of tasks should be prepared. The tasks should be grouped into the four categories, lot removal tasks, preparation tasks, changeover tasks and post-setup tasks. After preparing the list, it should be reviewed by the setup operator. The operator can determine if the list is complete.

1.2 Documenting Setups

Purpose: Before any recommendations or solutions can be made, several machine setups must be observed and documented. It is recommended that a minimum of 10 setups are documented. The purpose of recording this many setups is to determine how much time is needed to complete a task.

Personnel Required: An industrial engineer or someone familiar with time study methods should document the setups. Also, it is recommended that the documented machine changeovers are done by any experienced setup operator. If an inexperienced operator is studied, the resulting time standards may not be valid.

Process: Table 41 on page 155 outlines how documentation should be collected. The first step is to create a standard documentation form as shown in Figure 31 on page 156. The purpose of this form is to standardize the documentation. This will be helpful if more than one individual collects data. Also, all of the necessary information should be properly collected if the forms are used.

The first two columns on the form define the setup tasks and when they are performed. The tasks are chronologically listed. If the order of some tasks are not important, they are given a letter. For example, step 1 must be completed before step 2. However, step 1B can be done before or after steps 1A or 1C. The third column indicates if the task was performed at the machine area. If so, a check is placed in this column. The fourth column indicates if the task was performed by someone other than the setup operator. The fifth column records how much time was spent (in minutes) completing the task. Finally, the last column provides space to note any particular problems that may have occurred.

Table 41. Documenting Machine Changeovers

1. Create documentation form
2. Observe & record a minimum of 10 setups *

* Partial or full setups can be used. It is important that 10 or more readings are collected for each setup task.

After creating the documentation form, ten or more machine setups should be observed. Again, it is recommended that the setups are directly observed. As stated in Table 41, partial or complete setups can be studied. However, ten or more readings for each element are needed.

1.3 Establishing Standard Times

Purpose: A base time is assigned to each element. The base times are not an average of the observed times but an agreed standard time. The purpose of this section is to define a procedure to calculate this time.

Machine: ____________ Date: ____________
Operation: ____________ Operator: ____________
Start S/U: ____________ Finish Time: ____________
End Production: ____________

#	TASK	ON SITE	BY S/U OPER	TIME (min.)		PROBLEMS & COMMENTS
1A	Complete paperwork.	N	Y	9:25	5	
1B	Get incoming work	N	Y	9:30	5	
1C	Get tooling.	N	Y	9:40	10	
1D	Get spindle	N	Y	10:00	20	Spindle was misplaced
1E	Get gaging	N	Y	10:03	3	
1F	Count and remove old lot	N	Y	10:10	6	Very small lot (30)
2	Contact gage setter	N	Y	10:04	1	
3	Set shoes	Y	Y	10:12	9	
4	Remove guards, main unit, driver and internal gage	Y	Y	10:32	20	Stripped screw 10 minute delay
5	Change spindle	Y	Y	10:46	14	
6	Change quill	Y	N	10:50	4	
7	Build main unit	Y	Y	10:08	18	
. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .

Figure 31. Sample Documentation Form

Personnel Required: Because the base times may later be used as standards, they must be developed and approved by setup operators, area supervisors and industrial engineers.

Procedure: The procedure to establish base times may require some dialogue between operators, supervisors and industrial engineers. Initially, the industrial engineer should review the documented setups to determine a rough standard time per element. The standard time does not need to be the average time per element. Instead, it should be the time needed to complete the task without any problems. The average time may not be desired. If one of readings was significantly larger than the others, it will increase the overall average time. Also, it is an accepted rule that standard times do not include allowances for problems.

The standard times should include allowances for operator personal time and fatigue. Several companies use a 12.5% allowance. However, it may be desired to manually calculate an allowance. Two circumstances where a calculated allowance may be preferred over an accepted standard are when the operator performs tedious tasks or works in a harsh environment.

Table 42 on page 158 presents a list of allowances that were prepared by the International Labor Office [Salvendy, 1982.] Allowances exists for a number of variables such as heat, humidity, required lifting and the amount of mental concentration. A total allowance is found by adding the applicable allowances.

The list of standard times should be reviewed by the setup operators. The setup operators will tell the industrial engineer if any changes need to be made. Once an agreement about the standard times is reached, the list must be approved by the area supervisor.

Table 42. Allowances - International Labor Office

Allowance	Value (%)
Constant Allowances	
Personal allowance	5
Basic fatigue allowance	4
Variable Allowances	
Standing allowance	2
Abnormal position allowance	
Slightly awkward	0
Awkward (bending)	2
Very awkward (lying, stretching)	7
Use of force or muscular energy (lifting, pulling, or pushing)–weight lifted, in pounds:	
5	0
10	1
15	2
20	3
25	4
30	5
35	7
40	9
45	11
50	13
60	17
70	22
Bad light	
Slightly below recommended	0
Well below	2
Quite inadequate	5
Atmospheric conditions (heat and humidity)–variable	0–10
Close attention	
Fairly fine work	0
Fine or exacting	2
Very fine or very exacting	5
Noise level	
Continuous	0
Intermittent–loud	2
Intermittent–very loud	5
High-pitched–loud	5
Mental strain	
Fairly complex process	1
Complex or wide span of attention	4
Very complex	8
Monotony	
Low	0
Medium	1
High	4
Tediousness	
Rather tedious	0
Tedious	2
Very tedious	5

Section 2: Improve the Current Setup Procedure

Purpose: In the past, when lot sizes were large, machine changeover processes were rarely studied. It was believed that the benefits of reducing setup time would not be significant. As a result, inefficiencies in the setup process were allowed to exist. When the average lot size dropped, these problems became more noticeable. Examples of such problems are unnecessary wait time and an unstructured order of tasks.

For any machine, a number of changeover methods can exist. It is not uncommon to observe different setup processes for the same part. The number of alternative processes is dependent on the types of tasks that are performed. Some setup tasks must be completed before others. For example, new tooling cannot be installed without first removing the former set. Other tasks, such as getting tooling or retrieving gages, can be interchanged. If two different changeover processes are compared, the same number of tasks would be observed. However, the total setup time for each method may vary. The reason for this difference is some procedures are more efficient than others.

The objective of this section is to reduce setup time by restructuring the existing changeover procedure. The information presented in this section identifies which tasks can be completed in advance. Also, it reschedules the order of some tasks so that unnecessary idle time is avoided.

Personnel Required: An industrial engineer or an individual familiar with methods engineering should analyze the current setup process. After creating a new procedure, it must be reviewed and approved by both setup operators and area supervisors.

Procedure: There are two different types of setup elements, internal and external. An internal element is any task which must be done while the machine is stopped. An example of an internal element is changing a motor or machine belt. An external element is a task that can be performed while the machine is running. For example, tooling can be brought to the work area before the setup begins.

There are two phases in reorganizing the current setup process, separating internal and external elements and modifying the setup procedure so that any controllable idle time is avoided. The first step in separating internal and external elements is to identify which tasks can be performed while a machine is operating. Some guidelines on how to identify external elements are presented in Table 43. The second step is to determine which tasks can be done while the machine is operating and while using the current tooling and materials. Some of external tasks cannot be performed while the machine is running unless additional tooling is purchased or machine modifications are made. The justification process for purchasing or modifying equipment is discussed in Section 3.

Table 43. Guidelines for Identifying External Elements

- All lot removal and post setup tasks are external
- Most setup preparation elements are external
- Most external elements are at the beginning or end of a setup
- Tasks which are not in direct contact with the machine are external
- All tasks completed away from the work area are external
- Most tasks performed by other individuals are external

The second phase of writing a new method is to redefine the order of operations so that idle time is minimized. As stated earlier, there are a number of ways to changeover a machine. Some methods are more efficient than others. The purpose of this phase is to reorder the setup tasks to minimize any idle time.

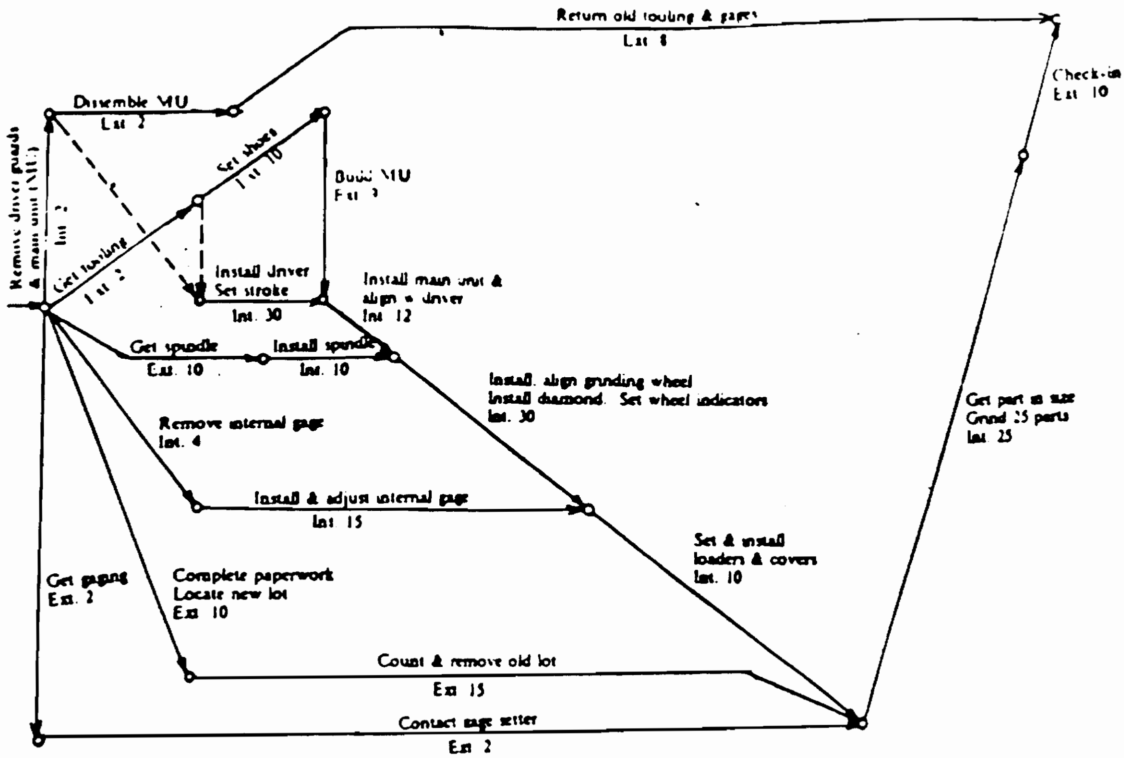
There are three steps to reschedule the order of setup tasks. First, determine which elements must be done before others and which can be interchanged. It should be asked why one task must be performed before another. Often, there may not be any reason except that the tasks have always been completed in that order. The second step is to identify which elements cause idle time. For example, if a part is sent to be inspected, some waiting may occur. The third step is to schedule the tasks so that idle time is minimized. This can be accomplished by completing other tasks, if possible, while waiting for others to be done. The new procedure should allow enough time to complete all external elements before production stops.

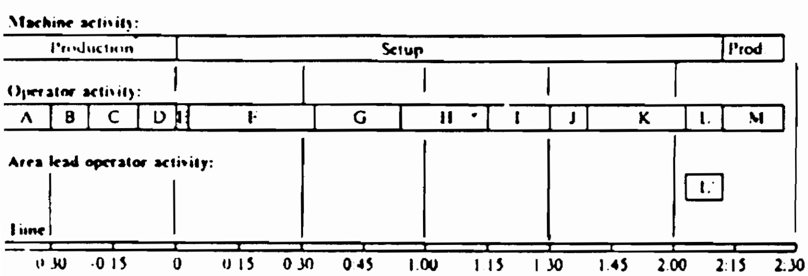
A network diagram or another visual tool should be used to create a new setup procedure. Internal and external elements should be distinguished on the diagrams. Examples of these charts are given in Figure 32 on page 162.

Section 3: Identify Setup Reduction Opportunities

Every system, including machine changeovers, consists of three components, manpower, a method and materials. To minimize machine down time, all three components must be as efficient as possible. Therefore, it is important that each component is addressed when reducing machine down time.

The purpose of this section is to present various methods to identify opportunities to reduce machine setup time. Section 3 consists of four sub-sections. Together, the four sub-sections identify potential opportunities to reduce setup time by considering the role of both labor, materials and the methodology of tasks completed at and away from the work area. Section 3.1 identifies opportunities to convert machinery or equipment so that it can be set while a machine is running. Section 3.2 identifies opportunities to improve or simplify setup materials. Section 3.3 presents a method to identify potential improvements for off-site elements. Finally, Section 3.4 identifies potential reductions in setup time by improving the use of labor resources.





Activity Key		
ID	Setup Task(s)	Time
A	Get tooling. Set shoes	12
B	Build main unit (MU)	9
C	Get gaging & lot	
	Complete paperwork	
	Contact gage setter	12
D	Get spindle	10
E	Remove driver, MU & guards	2
F	Install driver. Set stroke	30
G	Remove & set internal gage	[illegible]
H	Insall spindle	
	Install MU & align w driver	22
I	Install & adjust internal gage	
	Install & align grinding wheel	
	Install diamond. Set lights	45
J	Install loaders & covers	10
K	Count & remove old lot	15
L	Dissemble MU	2
M	Return old tooling & gages	8
N	Get part in size	
	Grind 25 parts	25
O	Check-in	10

Figure 32. Setup Gantt and Network Diagram Charts

3.1 Modifying the Setup Procedure

The main objective of a setup reduction project is to minimize machine down time. As stated in Section 2, one method to reduce down time is to complete portions of the setup while a machine is still producing parts. These types of tasks are called external elements. Internal elements are those tasks which must be done while a machine is stopped. Previously, it was shown that machine down time can be reduced by separating internal and external elements. Therefore, the purpose of this section is to identify opportunities to reduce machine down time by converting internal tasks into external tasks.

Purpose: There are two types of setup tasks, internal and external. Internal tasks must be completed while a machine is stopped. External tasks can be completed while a machine is running. Some tasks are termed internal because the current quantity or condition of some equipment prevents it from being external. If additional equipment is available or if machine/tooling modifications are made, a task can become an external element.

There are two methods to convert internal elements into external elements, function standardization and duplicate equipment. Function standardization modifies equipment so that it does not need to be regularly changed or adjusted. If duplicate equipment is available, additional tasks can be done in advance. The purpose of this section is to describe a method to identify such improvements.

Personnel Required: Industrial engineering should identify what improvements can be made and prepare an initial cost justification. These ideas must be approved by manufacturing engineering.

Procedure: Function standardization is modifying equipment so that it does not need to be regularly changed or adjusted. For example, consider changing a spindle motor. Some spindles operate at only one setting. As a result, it is routinely changed. If this motor is replaced with one that has multiple settings, it may not ever need to be removed.

Ideas for function standardization may or may not be obvious. To identify such improvements, a series of questions (Table 44), prepared by Productivity Inc. [1988], should be asked about each setup task. A list of improvements can be generated by answering these questions.

Table 44. Brainstorming Questioning

QUESTION	FOLLOWED BY	ACTIONS TAKEN
WHAT is the purpose?	Is this activity necessary? Can it be eliminated?	Eliminate unneeded task
HOW is this being done?	Why is it done this way? Is there a simpler way to perform the task? How should it be done?	Simplify or improve
WHERE is this being done?	Why at this location? Where should it be done?	Combine or change place
WHEN is this being done?	Why is this task done at this time? When should it be done?	Combine or change sequence
WHO is doing this?	Why is this person doing it? Who should do it?	Combine or change person

A second approach to convert internal elements into external is to have duplicate tooling or equipment available. Any subassembly or operation which is not in direct contact with a machine can be an external element. To determine what additional equipment is necessary, the following questions should be asked about each task:

- What tooling and equipment is used during the task?
- Can additional tooling or equipment become available?
- What modifications to the tooling, equipment or machine are needed so that it can be preset?
- What costs would occur?

After a list of improvements is prepared, justifications must be made. There are three steps to justify a proposed improvement. First, a study to determine the functional feasibility of the projects is completed. Second, the project costs and benefits are identified. A list of possible costs and benefits for both function standardization and purchasing additional equipment is presented in Table 45. Third, the proposals must be prioritized. A prioritization routine is explained in Section 4.

When any internal tasks becomes external, a new setup procedure must be written. The method to write a setup procedure is explained in Section 1.2.

Table 45. Benefit / Cost Analysis

Benefits	Costs
Shorten machine down time	Cost of purchasing equipment & tooling
Increase machine capacity	Cost of modifying machinery
Increase production	Cost of storing addition equipment
Improve worker safety (fewer tasks)	Training cost
Improve part quality (new equipment)	

3.2 Improving Setup Materials

Every system consists of three components, manpower, a methods and materials. Sections 2 and 3.1 discussed how machine down time can be reduced by improving the setup procedure or method. Section 3.3 will show the need to simplify off-site elements. Section 3.4 will address the importance of labor in setup reduction. This section will focus on how setup time can be further reduced by improving or repairing setup materials.

Setup materials are the tooling, machinery and equipment used to changeover a machine. They can range from a spindle motor to the clamps which hold it in place. It is possible to reduce both setup time and to prevent some problems from occurring by improving or repairing setup materials.

There are two methods to improve setup materials, reduce adjustment/clamping time and increase the reliability of the equipment. Each method is explained in detail in Section 3.2.1 and 3.2.2, respectively.

3.2.1. Reducing Adjustment / Clamping Time:

Purpose: Approximately 25 to 50 percent of the total setup time is spent adjusting or clamping an object [Hay, 1987]. Although these tasks are necessary, more efficient adjusting and clamping methods exist. Therefore, the purpose of this section is to identify where and how such improvements can be made.

Personnel Required: The procedure to modify clamps or adjustment methods can be simple or quite complex. As a result, justifications are necessary. Industrial and manufacturing engineers, area supervisors and other individuals must be involved in these projects.

Process: Making adjustments and clamping objects consume a significant portion of the total setup time. There are two reasons why these tasks take so long to complete. First, most machinery is designed for a wide range of settings. Even if only three settings are needed, the machine may have a much larger range. Second, most clamps are threaded. Although the traditional nut and bolt has a strong clamping force, it is inefficient. Only the last turn of the clamp holds the object in place. All other turns bring the nut and bolt closer together. Therefore, one can conclude that there is a need to simplify both adjustment and clamping methods.

There are two methods to reduce the time spent adjusting equipment. First, preset or permanent stops can be used to simplify adjustments. To illustrate this idea, consider an object in a machine that only needs two or three settings. If limit switches, stops or presetting fixtures are placed in the machine, a setup operator would immediately know if the object is correctly positioned. The second method to simplify an adjustment is to place calibrations or markings in the machine. Calibrations, such as ruler markings or center lines, help the operator determine where the correct positioning of an object is located. By using calibrations and/or preset stops, the time to adjust equipment is reduced.

Nearly every object inside a machine has some type of clamp. One of the most common clamps is the nut and bolt. As stated earlier, although threaded clamps provide a strong clamping force, they are inefficient.

Alternative clamping methods exist. These clamps can be significantly faster to use than a nut and bolt. However, before replacing any clamps, a detailed study must be performed to justify any changes. Three questions that must be answered are:

- Will the new clamp sufficiently hold an object?
- Have all constraints, such as space, been considered?
- Can the conversion costs be justified?

It is important that each clamp is analyzed to determine if it can sufficiently holds an object. If a weak clamp is used, problems will arise. Such problems include poor part quality, equipment failure and an unsafe working environment. Even if a clamp sufficiently holds a part, its space, power or other requirements may prevent the clamp from being implemented. For example, a power clamp was once considered to hold a spindle motor. The clamp was strong enough to prevent the motor from vibrating. However, because there was not enough space to mount the clamp, it could not be implemented. The final question that must be addressed is the conversion costs. Often, some machine modifications are necessary so that the clamp can be used. These costs must be included in the justification process.

The remainder of this section describes different clamping methods. A drawing and the purpose of various types of clamps is presented. The information presented in this section was taken from various quick changeover manuals [Productivity, 1988 and Shingo, 1985]. Other information can be obtained from manufacturing handbooks and catalogs.

One-Turn Attachments:

Pear-Shaped Hole Method: Standard circular bolt holes are replaced with pear shaped holes. Instead of loosening and removing each bolt, the bolts only need to be partially undone (one turn per bolt). When each bolt is loose, the object can be removed by sliding the larger opening over the bolt.

U-Slot Method: A u-shaped slot is cut into an object and a dovetail groove is put in the machine bed. The head of a bolt is placed in the groove. It is then moved along the groove and the u-shaped slot. Because the nut and bolt are pre-assembled before being placed in the groove, only one turn is necessary to clamp the object.

Split Thread Method: If a threaded clamp must be used, it is possible to modify it so that it can be tightened in one turn. Grooves can be cut in both the male and female ends of a threaded clamp. To attach the two objects, the ridges of one end are placed in the groove of another. The clamp is tightened by rotating it one-third of a turn. NOTE: Before implementing this method, the strength of the clamp should be tested. It has been found that the friction force can be increased by lengthening the screw.

U-Shaped Washer Method: For this method, the diameter of the nut is smaller than the hole. Objects are held together by the force exerted from a washer. Removing and replacing the nut is simplified by using a u-shaped washer. To remove the object, the bolt is rotated one turn. With the loosened bolt, the washer can be removed and the assembly can be replaced.

The Clamp Method: Nuts and bolts can often be replaced by a clamp. As shown in the figure, an external clamp is used to hold the object in place. The clamp is tightened or loosened by turning the setting screw one turn.

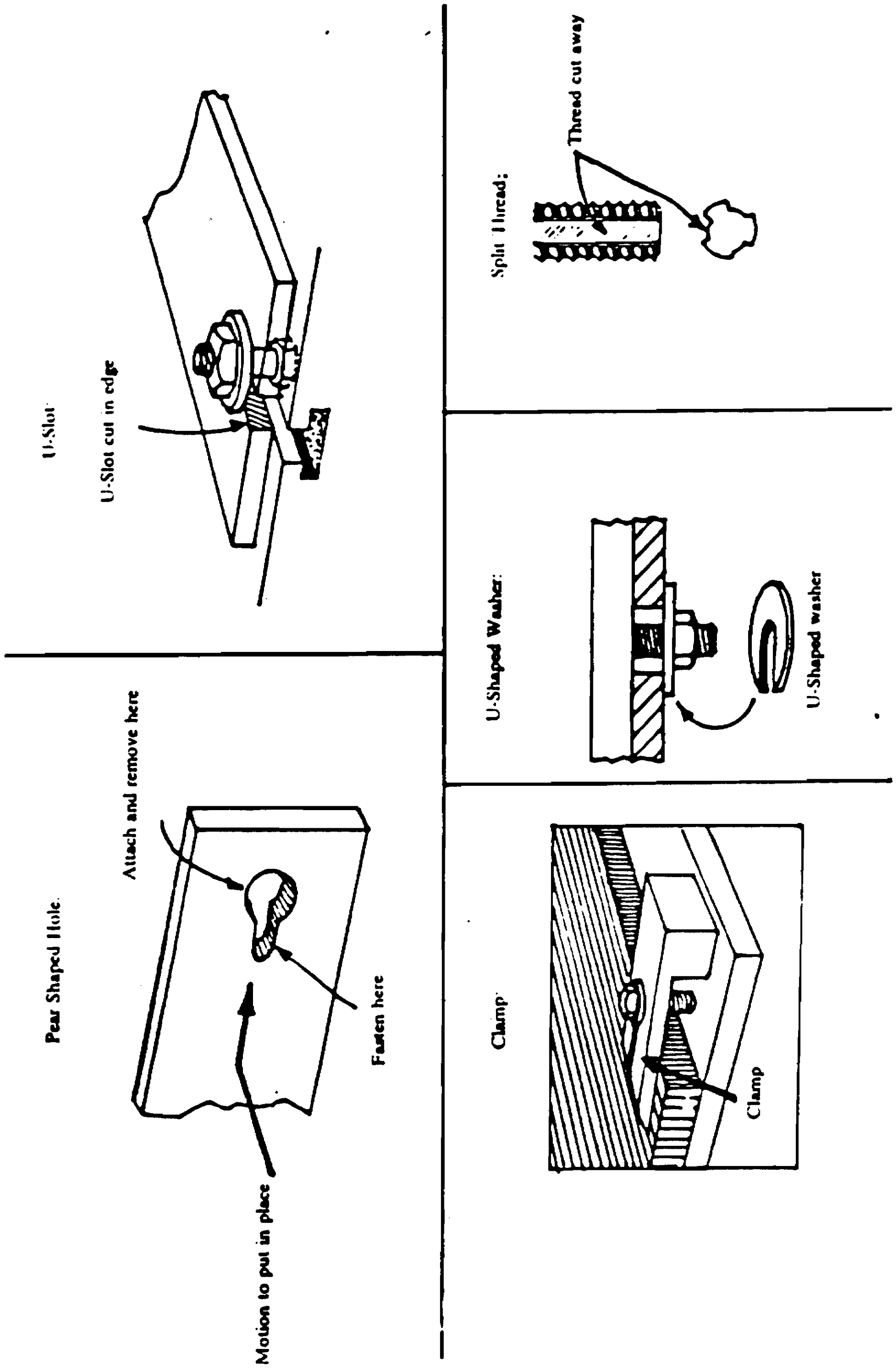


Figure 33. One Turn Clamping Methods

One Motion Methods:

A second type of quick release clamps is termed one motion clamps. This type of clamp secures an object by a single application of force. Unlike one turn attachments, one motion clamps require no rotational force.

There are five major types of one motion clamps, cams, springs, magnetic, vacuum and wedges/pins. Each type of clamp is simple to use and may shorten machine down time. However, before replacing any clamp, the function requirements for the new clamp must be checked. Otherwise, product quality and work safety may be jeopardized if an inadequate clamp is used.

Mechanized Methods:

A number of mechanized clamps exist. These clamps use an external power source such as electricity or hydraulics. Information about such clamps can be obtained from manufacturing handbooks or catalogs.

Mechanized clamps can provide a strong holding force. Also, they may reduce machine down time. Again, before replacing any clamp, function requirements for the new clamp must be checked. Some criteria includes the required clamping force, available space, power requirements and the time saved by using the mechanized clamp. If an inadequate clamp is installed, additional problems will arise.

3.2.2 Improving Equipment:

Purpose: There are three components in any system, manpower, a methodology and materials. If any component fails, the system, such as a machine changeover, stops. Therefore, it is important that all components are functioning properly.

Setup materials are any physical item going into the setup. These materials include each piece of tooling, clamp and the machine itself. Every type of material will eventually wear, distort or fail. If materials are not repaired or replaced in a timely manner, setup delays will occur. Therefore, the purpose of this chapter is to identify two methods to prevent such delays. The two methods are to (1) repair and replace broken equipment and (2) inspect equipment before starting a setup.

Personnel: Setup operators can readily identify what problems are occurring. Industrial engineers should analyze and evaluate the problems. Manufacturing engineers should determine how to correct the problems.

Manfacturing engineers, quality assurance and tool crib personnel should be involved in establishing policies and procedures to inspect tooling. Industrial engineering should identify the equipment which should be inspected.

Procedure: There are three steps to determine what equipment should be repaired or replaced: (1) determine what problems are occurring, (2) prioritize the problems and (3) repair or replace the equipment. Setup operators can identify what problems commonly occur. Because they regularly encounter these delays, operators should be able to give a rough estimate on the length and frequency of these problems. It is recommended that a wall chart (Figure 34 on page 172) or another type of data collection system is used to record the operator's information. The type of problem, its length and its frequency should be documented. Because it may be difficult for an operator give an exact measurement of a problem's frequency, it may be desired to have the operator state if a problem is rare, common or frequent. Also, a rough estimate of a problems length, such as an hour or two hours, can be used.

After a number of problems have been identified, they should be prioritized. A prioritization routine that considers these variables and others is presented in Section 4.

SETUP PROBLEMS

Machine: ____________________ Shift: ______________________

Problem	Date	Time Noticed	Time of Repair	Mach. Idle	Solution
Ex. Tooling not ready	3/13	10:30	11:00	10 min.	Issued expedite order
Ex. Driver unparallel w/ part	3/13	1:00	1:15	15 min.	Regrind driver

Figure 34. Setup Wallchart - Problem Identification

When the list is prioritized, it should be given to machine repair or engineering. To ensure future worker cooperation, the status of correcting broken or faulty equipment should be regularly told. It may also be desired to implement a worker incentive program so that future suggestions will be made.

Worker safety and morale may also increase by repairing broken or faulty equipment. Also, after correcting a number of problems, the average machine setup time and the amount of variation should decrease. The exact amount of time saved is dependent on the types of problems.

Another method to prevent equipment from failing during a machine changeover is to check its condition before the setup begins. Tooling can be checked by setup operators, tool crib personnel or other employees who can recognize equipment flaws. Although it can be checked at any time, equipment should be inspected after it is removed from the machine. If a flaw is found at this time, more time is available to correct it than if it were found just prior to the starting the setup.

3.3 Simplifying Off-Site Elements

Purpose: Off-site elements are those setup tasks which are not performed at the machine. Examples of such elements include building tool kits, preparing special gages or completing inspection tests. Often, these tasks are completed by another individual or by a service department.

Over the past few years, the average lot size has dropped while the average number of lots run per year have increased. As a result, more setups are being completed each year. This trend has increased the work load on service departments. If the capacities, methods or policies of these departments do not meet the current manufacturing demands, problems and/or delays will occur.

One source of setup time variation is from the delays caused by goods or services not being readily available. Examples of these types of delays are searching for incoming work, locating missing tooling and waiting for services. These delays can account for 5 to 50 percent of the machine setup time. Also, they may be the simplest to correct.

The purpose of this section is to identify opportunities to simplify off-site elements. Although each problem associated with these elements has an unique set of causes and effects, common traits exist. Therefore, a solution can be found by using and/or modifying one or more recommendations described in this section.

Personnel Required: Setup operators, personnel from service departments and industrial engineering should be involved in identifying significant problems with off-site elements. Industrial engineers and supervisors from manufacturing and service departments should participate in analyzing and correcting these problems.

Procedure: It is important to realize that all production problems, including off-site elements, can be corrected. It is often heard that a particular problem has always existed and that no feasible solution exists. This statement is merely an excuse. All capacity or queueing problems are by a company's own making. If a part must wait for inspection, then either there are not enough inspectors or the current system is ineffective. For either case, a solution is possible.

The procedure to identify and evaluate an off site element problem is defined in Table 46. The first step is to create a list of common problems. Once it is prepared, it should be verified by setup operators. Because the operators regularly encounter such problems, they will be able to tell if the problem is common or rare. At this time, all insignificant problems, such as those that occur once per year, should be removed from the list.

Table 46. Identifying Problems with Off-Site Elements

1. Identify common problems
2. Determine the frequency and length of each problem
3. Identify the most significant problems
4. Determine the problem causes

The second step is to collect data. Specifically, the length and frequency of various problems should be documented. This information can be obtained from historical data or direct observations. The study should note any cyclic trends. In some departments, the work load increases at the beginning or end of a month.

The third step is to prioritize the problems. A prioritization routine is explained in Section 4. The fourth step is to determine the fundamental cause of each problem. This information can be obtained by directly observing the problems, performing a random sample study, or interviewing workers and supervisors.

Although each problem has a unique set of causes, some common traits exist. These traits and possible solution methods are presented in Table 47 on page 176. By using or modifying one or more of these solutions, the length and frequency of an off-site element problem can be reduced.

3.4 Improving Labor Utilization

An important manufacturing resource is labor. For any type of system, there is some interaction between man and machine. Therefore, if the role of labor is not fully considered when designing or modifying a system, problems are almost inevitable.

The purpose of this section is to identify opportunities to reduce setup time by by making better use of labor resources. Section 3.4.1 explains the importance of setup instructions and guidelines. Section 3.4.2 defines a method which determines if machine down time can be reduced by using more than one operator.

3.4.1 Providing Setup Documentation:

Table 47. Problem sources and solutions

Problem	Causes	Solution
Undermanned	Lack of labor	Hire personnel Cross train Automate
	Work load varies (increase or decrease)	Evaluate scheduling/ordering methods
Lack of tooling	Understocked	Order more tooling to meet future needs
	Sitting idle on a holding site (advanced ordering exists)	Reduce ordering lead time or quantity State the pick up time
Long queues	Capacity	Improve the procedure Repair broken equipment Review the purpose of the test
	Undermanned	See above
	Lack of tooling	See above

Purpose: Some companies have little documentation about machine changeover procedures. As a result, setup operators may not thoroughly learn how to perform a machine setup. Also, if no instructions or documentation exist, excessive time may be spent by an operator trying to identify and correct a simple problem.

The solution to these problems is to provide documentation about the changeover process. Specifically, instructions and objective times are given to each operator. Also, a trouble shooting guide should be written for each machine. If such information is available, the machine down time can be reduced.

Personnel Required: Engineers and experienced setup operators should write the setup instructions and checklists. The instructions and trouble shooting manual need to be reviewed by manufacturing engineering, setup operators and supervisors.

Procedure: There are three forms of documentation that each setup operator needs, checklists, instructions and a trouble shooting guide. All three items can be simultaneously written.

A setup checklist is a list of operations that an worker should follow. This checklist is the changeover procedure that has been previously defined. The checklist states the standard completion time for each task. When the new method is introduced, it is recommended that the setup operators record the completion time of each element. Elements should be grouped into 10 or 15 minute blocks. If they are broken into smaller time frames, the forms may become a nuisance to the operator.

Figure 35 on page 178 is a sample checklist for an outer ring race grinding operation. The checklist defines which tasks must be done before others and which can be interchanged. The list shows how many minutes are needed to complete each task. It also asks the operator to record the completion time of each element and to indicate if any problems occurred. Finally, it shows if a change of operators has occurred.

Table 48 lists five benefits of using setup checklists. First, if setup operators are required to follow the scheduled order of operations and record the time each task was completed, the new method will be learned. Second, operator awareness may increase if they are required to use the forms. For some machine operations, the only allowance that is given to a worker is the total machine setup time. If the forms are used, a worker will know if the targeted completion time can be obtained throughout the setup. The operator will also know how much time should be allowed to finish each task.

The third benefit of using checklists is the probability of having tasks repeated is reduced. When a setup cannot be finished by a worker, another operator may repeat a completed task. There are two reasons why this occurs. First, the second operator may not know what tasks have been performed. Second, the latter worker may not trust the other setup operator. If each operator is held accountable for completing their part of the setup, the chances on having tasks repeated should be reduced.

Part: ________	Oper: ________	Machine: ____________
Name: ________ Shift: ________	Date: ________	Start Time: ____________ Stop Time: ____________
Name: ________ Shift: ________	Date: ________	Start Time: ____________ Stop Time: ____________

#	STEP	GOAL TIME	TIME USED	FINISH TASK?
1	Complete paperwork. Get parts. Get tooling.	12		
2	Get spindle	10		
3	Get gaging	2		
4	Set shoes	10		
5	Build 2nd main unit	14		
	END PRODUCTION			
6	Contact gage setter Count and remove old lot	2 15		
7	Remove guards, old main unit, driver and internal gage	6		
8	Change spindle	10		
9	Install and indicate driver	5		
10	Set stroke	15		
11	Install main unit and align driver to unit	12		
12	Install new wheel. Align wheel to part. Set diamond. Set wheel indicators.	30		
13	Set, install and adjust internal gage	33		
14	Set and install loaders. Return covers.	10		
15	Get part within size. Grind 25 good parts.	25		
16	Check-in (by area lead man)	10		
	BEGIN PRODUCTION			
17	Return old tooling and gaging	8		

Figure 35. Sample Setup Checklist

The fourth benefit is the identification of specific skill deficiencies. For example, if three workers take 10 minutes to complete a task, another operator should not take 15 minutes. The checklist can be useful when training new workers as well. The final benefit of using the checklists is additional data for future projects can be collected. Specifically, information about the length and frequency of any problem can be recorded on the lists. This information can be used to justify future projects or purchases.

Table 48. Checklist Benefits

- Promotes a standard changeover process
- Increases operator awareness
- Eliminates repeated tasks
- Identifies labor skill deficiencies
- Collects additional data

Besides having checklists, setup instructions and a trouble shooting guide should also be given to each operator. Questions and/or problems will arise. Unless the operator is experienced, an incorrect or inefficient solutions may be attempted.

Setup instructions should be written by an individual who is very familiar with the changeover process. To be consistent with other setup documentation, instructions should be written for each setup element that appears on the checklist. Each set of instructions must be reviewed and approved by manufacturing engineering, area supervisors and the setup operators. Also, it is very important that setup operators understand the document. If they are not clearly written, the instructions will not be used.

There are two purposes in creating a trouble shooting guide. First, the guide helps setup operators quickly identify the cause of a problem. Second, the probability of using the wrong solution to correct a problem can be reduced.

Writing a trouble shooting guide is a continuous process. New problems are inevitable and must be documented. Each setup operator should keep a log book. This book contains forms

(Figure 36 on page 181) which record each problem's symptoms, location, cause, and solution method.

When a form is completed, it should be reviewed by manufacturing engineering or machine repair to validate the solution method. The form should be rewritten and included in each setup operator's trouble shooting guide.

3.4.2 Determining the Optimal Operator to Machine Ratio:

Purpose: It is often assumed that only one setup operator can changeover a machine. However, depending on the type of machine and setup tasks, it may be possible to have more than one operator. Therefore, the objective of this section is to define a method which determines how many operators should be assigned to a machine changeover.

Personnel Required: An individual familiar with Gantt charts and line balancing can calculate the optimal number of setup operators. The results must then be justified to the area supervisor and/or management.

Procedure: To determine how many setup operators should changeover a machine, various operator-to-machine schedules should be created and evaluated. Network charts and Gantt charts can be useful in developing a new setup schedule.

A network diagram is a pictorial representation of the setup process. As shown in Figure 32 on page 162, each line represents a setup activity. Each node, shown as a circle, is a point in time. Before any task can be started that originates from a node, all tasks going into it must be completed. For example, before one can change a motor belt, the machine must be stopped and a new belt is brought to the machine. A network diagram should be drawn for the changeover process. The purpose of this chart is to ensure that a new schedule does not make any incorrect assumptions.

Problem: ____________________

____

Tool / Item: ____________________

____

Symptoms: ____________________

____

____

____

____

Solution: ____________________

____

____

____

____

____

____

Who to contact: ____________________

____

Related Problems: ____________________

____

____

____

Figure 36. Trouble Shooting Guide Form - Example

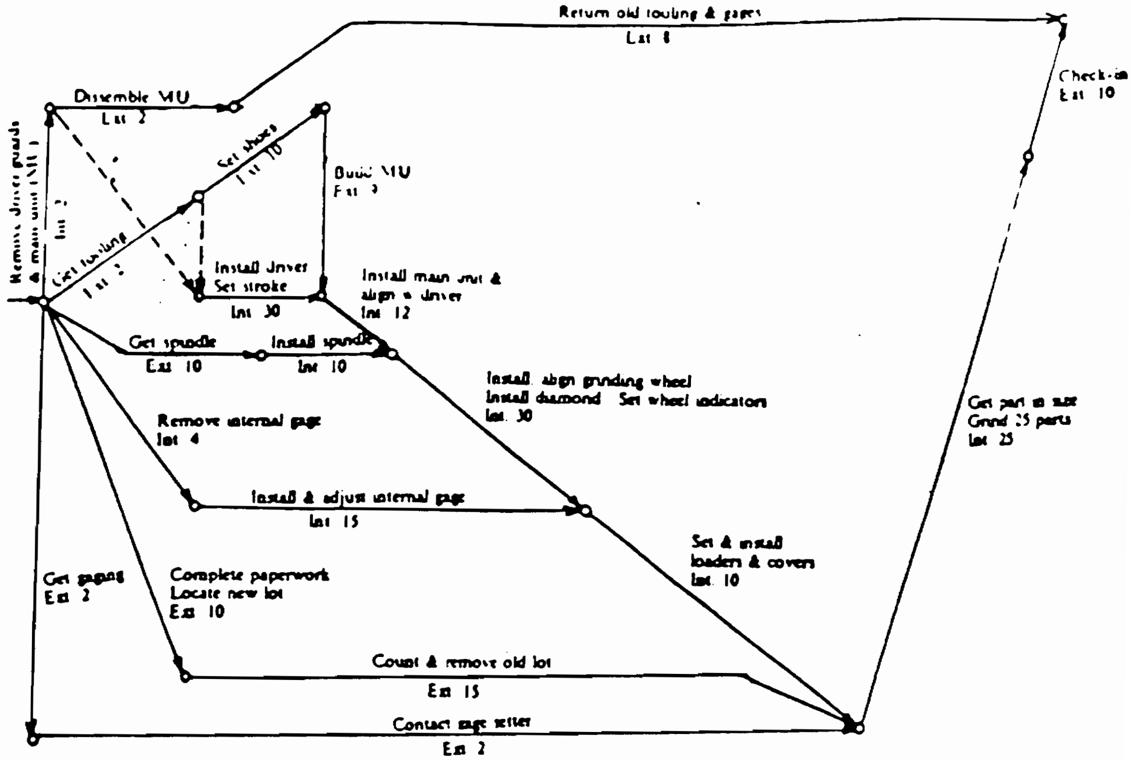
A Gantt chart is a horizontal time bar chart that shows when tasks are completed in relationship to others. The objective of a Gantt chart is to define a schedule for completing a series of tasks in the least amount of time. Often, the schedule is subject to some resource constraint, such as labor.

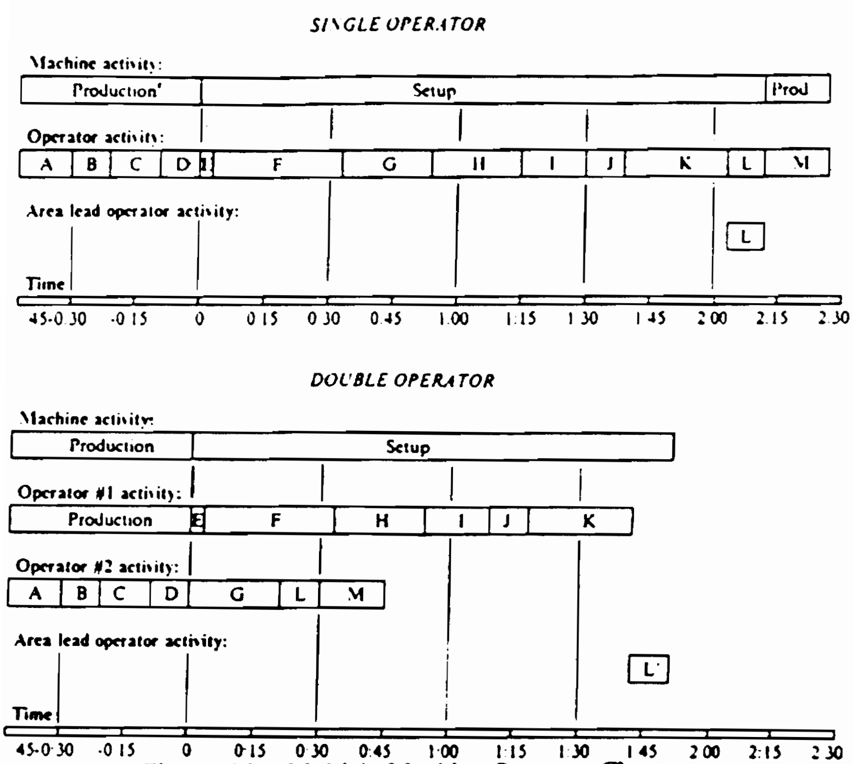
There are 4 steps to determine how many setup operators should be used. First, a list of setup tasks and standard times is reviewed. The list should indicate which tasks must be completed before others and which can be interchanged. Second, a line and node chart is drawn. Third, a multiple operator chart is created as shown on Figure 37 on page 183. The X-axis represents time in minutes. The Y-Axis represents the number of setup operators.

The fourth step is to create a schedule for each setup operator. A set of setup tasks is to be assigned to an operator. On the chart, each task is denoted by a bar and should be labeled. It is important that the rules in Table 49 on page 182 are followed. After creating the chart, the total setup time can be calculated. This process should be completed for using 1, 2 or more operators until an optimal, yet feasible, schedule is found.

Table 49. Rules for Creating Setup Time Gantt Charts

- Minimize idle time.
- Minimize waiting.
- Try to make the work load for each operator equal.
- Include both internal and external elements.
- Consider space constraints. For example, two tasks may be interchangeable. However, because there is only enough room for 1 worker, the tasks cannot be simultaneously scheduled.
- A second or third operator does not have to be at the machine for the entire setup.
- Two setup operators can work on the same task.
- Keep at least one worker at the machine at all times.





Activity Key		
ID	Setup Task(s)	Time
A	Get tooling. Set shoes	12
B	Build main unit (MU)	9
C	Get gaging & lot Complete paperwork Contact gage setter	12
D	Get spindle	10
E	Remove driver, MU & guards	2
F	Install driver. Set stroke	30
G	Remove & set internal gage	[illegible]
H	Insall spindle Install MU & align w driver	22
I	Install & adjust internal gage Install & align grinding wheel Install diamond. Set lights	45
J	Install loaders & covers	10
K	Count & remove old lot	15
L	Dissemble MU	2
M	Return old tooling & gages	8
N	Get part in size Grind 25 parts	25
O	Check-in	10

Figure 37. Multiple Machine Operator Charts

Section 4: Prioritize the Setup Reduction Opportunities

Purpose: When conducting a setup reduction project, a number of opportunities to reduce setup time are identified. These benefits of each opportunity can vary in both length and frequency. Each opportunity may initially appears to warrant implementation. However, constraints exists which may limit the number of projects that can be implemented. Usually, there is a limit as to the amount of capital or available manpower that can be spent to correct setup problems. Therefore, a method to determine which opportunities are most beneficial was developed.

There are two main objectives of this chapter. First, a method is presented that identifies management objectives of the setup reduction project. Second, a method is presented which prioritizes setup reduction opportunities with respect to management objectives.

Personnel Required: Management, including directors of production and manufacturing, should provide information about company objectives. Their input will be used by the coordinator of the setup reduction project to calculate weights for the objectives.

Procedure: The routine that priorizes setup reduction opportunities incorporates some of the principles of the Brown Gibson model [Canada and Sullivan, 1989] and the analytic hierarchy process (AHP) [Saaty, 1985]. The prioritization routine consists of four steps: (1) identify relevant criteria, (2) establish preference weights for each criteria, (3) develop an evaluation scale for each criteria and (4) evaluate and prioritize the setup reduction opportunities using the selected criteria. Each step will be described in detail.

The prioritization routine can be used in other machine cells. However, both the criteria and the weights should be updated to reflect the objectives of each setup reduction project. If any item becomes obsolete, the results of the prioritization routine will be invalid.

Step 1 Identifying Relevant Criterion:

The prioritization routine decomposes an opportunity to reduce setup time into several attributes. The method uses a hierarchy (Figure 38 on page 186) to define significant attributes and subattributes. The top level of the hierarchy is the overall objective which is to reduce setup time. The second level of the hierarchy is the general criterion classifications. There are two classifications of attributes or criterion, objective and subjective. An objective criteria is one which can be directly measured, such as time. A subjective criteria is one cannot be easily quantified, such as improving worker safety. Although objective criterion are traditionally used in making justifications, it is important that subjective criteria are included. Otherwise, important benefits may be overlooked.

The third level of the hierarchy are the specific attributes that are used to evaluate the opportunities. Some relevant objective and subjective criteria are listed in Table 50. The final level of the hierarchy are the various alternatives or opportunities that will be evaluated with respect to each criteria.

The coordinator of the setup reduction project or management can select a set of relevant criteria from the table. Other criteria can also be used. However, it is important to include only significant, independent, and relevant criteria. If too many measures are used, it will become cumbersome to develop weights and/or evaluate different proposals.

Table 50. Revelant Criteria - Prioritization Routine

Objective Attributes	Subjective Attributes
• Problem length	• Worker safety
• Problem frequency	• Ergonomics
• Correction cost	• Product quality
• Time to correct the problem	• Equipment maintainability
• Setup scrap	• Work enhancement

Step 2 Establishing Criteria Weights:

Preference weights are calculated for each criteria. The larger the value, the more important the

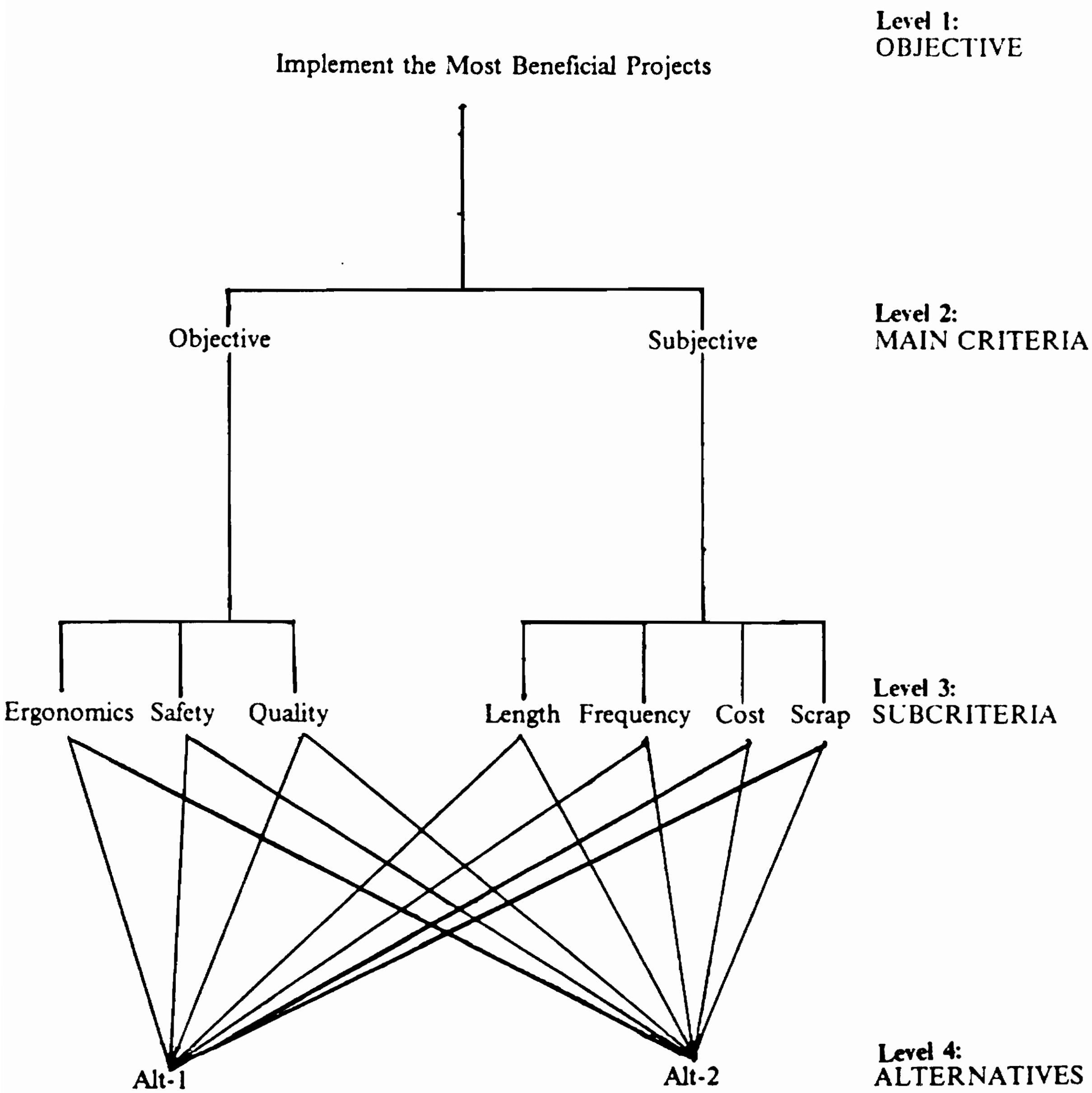


Figure 38. Criteria Hierarchy - Prioritization Routine

criteria is with respect to the overall objectives of the setup reduction project. The prioritization routine uses the pairwise comparison method that Saaty [1985] presents in AHP to calculate criteria weights.

There are six steps to calculate criteria weights. The first step is to prepare a matrix of paired comparisons for both objective and subjective criteria. Key individuals (management) are asked to evaluate each alternative with respect to the others. Figure 40 on page 189 is a sample form to document the results. From their responses, a matrix is created (Figure 39 on page 188). The row and column headings are the objective or subjective attributes. Each value in the matrix is the preference ratings of the row attribute compared to a column attribute. All of the values along the diagonal (the preference rating of an attribute compared to itself) must be 1.0. Also, the value of each comparison, x_{ij} must be the inverse of the corresponding comparison, x_{ji}. For example, (see Figure 39), the correction cost is more important than the time needed to correct a problem. Therefore, a value of 3 is assigned when cost is compared to the correction time. Also, a value of 1/3 is assigned when the correction time is compared to the cost.

Table 51. Preference Comparison Scale - Prioritization Routine

Value	Preference
1	Both attributes are equally preferred
2	Attribute x is preferred over y
4	Attribute x is strongly preferred over y
6	Attribute x is absolutely more important than y

The second step is to normalize the values in each matrix column. When a column is normalized, the sum of its values equal 1.0. Normalization is achieved by dividing each number in a column by the corresponding column sum. The third step is to total the values in each row. The results are used to create a vector (see Figure 39 on page 188). The fourth is to normalize this vector. The normalized vector is the priority weights.

Step 1: Create the initial preference matrices and calculate the sum of each column.

Objective Attributes

	L	F	C	T
L	1	1/3	2	2
F	3	1	4	4
C	1/2	1/4	1	1
T	1/2	1/4	1	1
Total	5	1.833	8	8

Subjective Attributes

	Q	S-E
Q	1	1
S-E	1	1
Total	2	2

L = Problem length
F = Problem frequency
C = Anticipated correction cost
T = Estimated time to correct the problem

Q = Quality
S-E = Safety and Ergonomics

Step 2: Normalize each column so that its sum equals to 1.0.
(Divide each number by its column sum.)

Objective Attributes

	L	F	C	T
L	0.200	0.182	0.250	0.250
F	0.600	0.545	0.500	0.500
C	0.100	0.136	0.125	0.125
T	0.100	0.136	0.125	0.125

Subjective Attributes

	Q	S-E
Q	0.500	0.500
S-E	0.500	0.500

Step 3: Calculate the matrix eigenvector.
(Add the values of each row)

Objective Attributes

	L	F	C	T	Vector
L	0.200	0.182	0.250	0.250	0.882
F	0.600	0.545	0.500	0.500	2.145
C	0.100	0.136	0.125	0.125	0.486
T	0.100	0.136	0.125	0.125	0.486

Subjective Attributes

	Q	S-E	Vector
Q	0.500	0.500	1.000
S-E	0.500	0.500	1.000

Step 4: Normalize the vector to get the attribute weights.
(Divide each number by the vector sum.)

Objective Attributes

L	0.2206
F	0.5364
C	0.1215
T	0.1215

Subjective Attributes

Q	0.5000
S-E	0.5000

Figure 39. Calculating Preference Weights - Example

Directions:

1. Determine which of the two attributes is preferred.
2. Using the scale presented below, circle the number number which best reflects the attribute's preference the attribute's preference over the other

Example:

Attribute	Value	Attribute
Red	6 5 4 3 2 1 2 3 (4) 5 6	Blue

Blue is strongly preferred over red.

OBJECTIVE MEASURES

Attribute	Value	Attribute
Length	6 5 4 3 2 1 2 3 4 5 6	Frequency
Length	6 5 4 3 2 1 2 3 4 5 6	Cost
Length	6 5 4 3 2 1 2 3 4 5 6	Time
Frequency	6 5 4 3 2 1 2 3 4 5 6	Cost
Frequency	6 5 4 3 2 1 2 3 4 5 6	Time
Cost	6 5 4 3 2 1 2 3 4 5 6	Time

SUBJECTIVE MEASURES

Attribute	Value	Attribute
Quality	6 5 4 3 2 1 2 3 4 5 6	Safety & Ergonomics

OVERALL COMPARISON

Attribute	Value	Attribute
Objective	6 5 4 3 2 1 2 3 4 5 6	Subjective

Scale:

Value	Significance attribute x is .... attribute y
1	equally important as
2	generally preferred over
4	strongly preferred over
6	absolutely more important than

Figure 40. Sample Attribute Preference Documentation Form

The fifth step is to review the results. Thomas Saaty present a consistency ratio test to verify the results. The consistency ratio test and an example is presented in Figure 41 on page 191. If the results are inconsistent, the data needs to be reviewed. Usually, the most common mistakes are the assignment of preference values. If two attributes are equally preferred, their comparisons with other attributes must be identical. A second mistake is logic. If attribute A is preferred over B and attribute B is preferred over C, attribute A must be preferred over C. Also, the magnitude of A over C must be greater than A over B. After identifying the error, the survey can be redistributed or the data can be corrected.

The final step in creating preference weights is to determine an overall preference weight between objective and subjective measures. Again, individuals are asked to use the scale presented in Table 51 on page 187 to evaluate the two measures. The weight for the each measure is:

Preferred criteria: Weight $= W_p = \dfrac{n}{n + \frac{1}{n}}$

Weaker criteria: Weight $= W_w = 1 - W_p$

where n = Preference value

W_p = Weight for the preferred criteria

W_w = Weight for the weaker criteria

The resulting numbers are the preference weights. Before using these numbers, they should be reviewed and modified if needed.

For example, if objective attributes were strongly preferred over subjective attributes, a factor 2 would be assigned. The corresponding criteria weights would be:

Objective attribute weight $= W_p = \dfrac{2}{2 + \frac{1}{2}} = 0.80$

Subjective attribute weight $= W_w = 1 - 0.80 = 0.20$

Step 1: Multiply the initial preference matrix by the calculated priority weights.

Objective Attributes

	Preference Matrix L	F	C	T	Priority Weights	Results
L	1	1/3	2	2	0.2206	0.8854
F	3	1	4	4	0.5364	2.1702
C	1/2	1/4	1	1	0.1215	0.4874
T	1/2	1/4	1	1	0.1215	0.4874

Subjective Attributes

	Preference Matrix Q	S-E	Priority Weights	Results
Q	1	1	0.5000	2.0000
S-E	1	1	0.5000	2.0000

Step 2: Divide the each number in the resulting vector by its corresponding priority weight.

Objective Attributes **Subjective Attributes**

$$\left| \frac{0.8854}{0.2206} \;\; \frac{2.1702}{0.5364} \;\; \frac{0.4874}{0.1215} \;\; \frac{0.4874}{0.1215} \right| \qquad \left| \frac{1.0000}{0.5000} \;\; \frac{1.0000}{0.5000} \right|$$

$$= \; | \; 4.0136 \;\; 4.0459 \;\; 4.0115 \;\; 4.0115 \; | \qquad | \; 2.0000 \;\; 2.0000 \; |$$

Step 3: Calculate the average (μ) of this new vector.

Objective Attributes = 4.0206
Subjective Attributes = 2.0000

Step 4: Calculate the consistency index (CI) for the vector of size N using the formula:

$$CI = \frac{\mu - N}{N - 1}$$

$$\text{Objective Attributes} = \frac{4.0206 - 4}{4 - 1} = 0.006875$$

$$\text{Subjective Attributes} = \frac{2.0000 - 2}{2 - 1} = 0$$

Step 5: Calculate the consistency ratio by dividing CI by the correct random index (RI)

N	RI
2	0.00
3	0.58
4	0.90

N	RI
5	1.12
6	1.24
7	1.32

N	RI
8	1.41
9	1.45
10	1.49

N	RI
11	1.51

Objective Attributes: CR = 0.006875/0.90 = 0.0076
Subjective Attributes: CR = 0.000

If the calculated CR is less than or equal to 0.1, the initial preferences are considered to be reasonably consistent.

Figure 41. Consistency Ratio Test

Step 3 Developing Criteria Measurement Scales::

For each criterion or attribute, the coordinator of the setup reduction project should develop a scale (with input from management) to evaluate setup reduction opportunities. The numeric values must be consistent between attributes. Table 52 defines a proposed scale of attribute values. Other values can be used. However, it is important that the scale of values is neither too broad nor too narrow.

Table 52. Criteria Scale - Prioritization Routine

Value	Significance
1	The problem should not be addressed
3	The problem is worth mentioning
6	The problem should be corrected
9	The problem must be corrected

For the objective measures, discrete numeric ranges are to be assigned for each value. For example, Table 53 presents four hypothetical attributes and the ranges for each scale value.

Table 53. Hypothetical Criteria Scale - Objective Attributes

	Frequency		**Cost**
Value	Range	Value	Range
1	Less than 5% of all setups	1	Over $20K
3	Between 5% and 20% of all setups	3	$10K - $20K
6	Between 20% and 50% of all setups	6	Under $10K
9	Over 50% of all setups	9	No cost
	Length		**Correction Time**
Value	Range	Value	Range
1	Less than 1% of the total setup time	1	Over 6 months
3	Between 1 - 5% of the total setup time	3	Between 1 and 6 months
6	Between 5 - 10% of the total setup time	6	Between 1 and 4 weeks
9	Over 10% of the total setup time	9	Less than a week

For the subjective measures, discrete numeric ranges are difficult to develop. Instead, the proposed scale in Table 52 on page 192 was modified to develop an evaluation scale (Table 54). The proposed scale is based on the same 1 - 9 scale used to evaluate objective measures.

Table 54. Criteria Scale - Subjective Attributes

Value	Significance
1	No improvements are possible
3	Indirect or minor improvements are possible
6	Improvements are expected
9	Major improvements are expected

Step 4 Prioritizing Setup Reduction Opportunities:

The developed prioritization routine uses some concepts of the Brown-Gibson model to evaluate opportunities. Each opportunity is evaluated with respect to every objective and subjective attribute. A combined score is calculated that uses the previously defined attribute weights and values. The opportunities with the largest scores should be promptly implemented.

There are five steps to calculate the combined score (see Figure 42 on page 194.) The first step is to evaluate each idea with respect to each attribute. A value is assigned to each setup reduction opportunity from the range of attribute values (1 - 9). The second step is to normalize the values with respect to each attribute. The third step is to multiply each number by its corresponding attribute weight.

The fourth step is to separately total the objective attribute values and the subjective attribute values. Again, these numbers are multiplied by their corresponding preference weight. The final step is to add the weighted objective and subjectives values to get a total score for each proposed idea.

There are three advantages of using this approach to prioritize setup reduction opportunities. First, the evaluation process is simple to use and understand. Second, the evaluation method allows the user to see the contribution of each objective and subjective attribute in the final score. For example, part inspection delays were more frequent than electrical problems. Third, because the contribution of each attribute in known, the expected results of implementing a project can be

1. Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES Length	Frequency	Cost	Time	SUBJECTIVE ATTRIBUTES Quality	Safety Ergon.
1. Electrical	9	1	1	1	6	3
2. Drivers	9	1	3	1	6	1
3. Find lot	9	3	9	3	1	1
4. Get tooling	3	3	6	3	3	1
5. Get gages	9	3	1	3	3	1
6. Part insp.	9	9	1	3	3	1

2. Normalized Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES Length	Frequency	Cost	Time	SUBJECTIVE ATTRIBUTES Quality	Safety Ergon.
1. Electrical	0.1875	0.0500	0.0476	0.0714	0.2727	0.3750
2. Drivers	0.1875	0.0500	0.1428	0.0714	0.2727	0.1250
3. Find lot	0.1875	0.1500	0.4286	0.2143	0.0454	0.1250
4. Get tooling	0.0625	0.1500	0.2857	0.2143	0.1364	0.1250
5. Get gages	0.1875	0.1500	0.0476	0.2143	0.1364	0.1250
6. Part insp.	0.1875	0.4500	0.0476	0.2143	0.1364	0.1250

3. Weighted Evaluation

PROBLEM	OBJECTIVE ATTRIBUTES Length 0.2206	Frequency 0.5364	Cost 0.1215	Time 0.1215	SUBJECTIVE ATTRIBUTES Quality 0.5000	Safety Ergon. 0.5000
1. Electrical	0.0414	0.0268	0.0058	0.0087	0.1364	0.1875
2. Drivers	0.0414	0.0268	0.0178	0.0087	0.1364	0.0625
3. Find lot	0.0414	0.0805	0.0521	0.0260	0.0227	0.0625
4. Get tooling	0.0138	0.0805	0.0347	0.0260	0.0682	0.0625
5. Get gages	0.0414	0.0805	0.0058	0.0260	0.0682	0.0625
6. Part insp.	0.0414	0.2414	0.0058	0.0260	0.0682	0.0625

4. Total Objective & Subjective Measures

PROBLEM	OBJECTIVE ATTRIBUTES	SUBJECTIVE ATTRIBUTES
1. Electrical	0.0827	0.3239
2. Drivers	0.0942	0.1989
3. Find lot	0.2000	0.0852
4. Get tooling	0.1550	0.1307
5. Get gages	0.1537	0.1307
6. Part insp.	0.3146	0.1307

5. Weighted Objective & Subjective Measures and the Total Score

PROBLEM	OBJECTIVE ATTRIBUTES (0.70)	SUBJECTIVE ATTRIBUTES (0.30)	TOTAL SCORE
1. Electrical	0.0579	0.0972	0.1551
2. Drivers	0.0659	0.0597	0.1256
3. Find lot	0.1400	0.0256	0.1656
4. Get tooling	0.1085	0.0392	0.1477
5. Get gages	0.1076	0.0392	0.1468
6. Part insp.	0.2202	0.0392	0.2594

Figure 42. Example - Evaluating Setup Reduction Opportunities

predicted. For example, machine down time will be reduced further by shortening part inspection compared to improving the process of retrieving tooling.

Section 5: Project Implementation

The final step of the method is to implement the prioritized setup reduction opportunities. Because a variety of setup reduction projects can be implemented, there is no single technique that can be used to implement every project. Therefore, the purpose of this section is to present some general implementation guidelines.

Projects can be simultaneously implemented. For example, while manufacturing engineers redesign a tool fixture, industrial engineers can begin collecting data for a project to reduce part inspection queues.

One individual or department should be responsible for monitoring the progress of each project. This individual should schedule meetings with the appropriate personnel to discuss the status of each project. Also, this individual should document the implementation procedure, the encountered problems and solutions, and the resulting project benefits. This information may be useful when other projects are implemented.

Setup operators should be included at progress meetings and receive status reports. These operators are more familiar with the changeover procedure than any other personnel. By including these individuals throughout the implementation process, their knowledge and cooperation can be more easily obtained. Also, allowing employees to participate in the setup reduction project may increase morale.

Vita

Paul Michael Szatkowski was born on December 9, 1966, in Detroit, Michigan. He is the oldest child of Paul R. and Diana Szatkowski. After moving five times, his family settled in Bethel, Connecticut. There, he graduated from Bethel High School in 1984.

In the fall of 1984, he enrolled at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. In 1988, he received a Bachelor of Science degree in Industrial Engineering and Operations Research. He also completed a minor in History. In 1990, he received a Master of Science degree in Industrial Engineering and Operations Research from the said university.

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