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METHODS FOR REDUCING CHANGEOVER TIMES THROUGH SCHEDULING

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BY

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ABSTRACT

To compete in today's manufacturing markets, it is necessary to have diverse product lines that can be manufactured and delivered to the customer in the shortest time possible. Producing a large range of products in a short amount of time is only possible through efficient and effective manufacturing practices. One way to improve the efficiency of a manufacturing system is to reduce the time required to change from product "A" to product "B". This will decrease the lead time of the product and increase the overall equipment effectiveness for the equipment used to process the product. Decreasing the time required to change between the manufacture of two products is known as changeover reduction.

In this thesis three strategies are described for reducing changeover times for vertical CNC milling machines for a company that manufactures industrial equipment. The first changeover reduction strategy is focused on the implementation of the single minute exchange of die methodology. This method is widely used throughout the manufacturing industry as a systematic, and extremely effective, way to decrease changeover times. The setting of this research provided an excellent opportunity to implement the methodology.

The second strategy developed a way to schedule all of the components of the same product so that the components are processed during the same time period. The third strategy utilized the rank order clustering algorithm to create a schedule that organizes jobs into groups that share similar changeover activities, such as the required tools and fixtures.

After observing and analyzing six changeovers, a methodology was developed to arrange the changeover tasks in order to maximize the manufacturing time of the CNC milling machines. Applying the proposed changeover methodology to one of the analyzed changeovers shows that a significant reduction in changeover time is possible. It was also found that scheduling components of the same product so that they are produced in the same time period reduces the overall changeover time of the product. Lastly, applying the rank order clustering algorithm reduced the number of tool and fixture changeovers.

If the methods described in this thesis are implemented, then a reduction in changeover time should be seen. Applying the discussed methods will also result in improved overall equipment effectiveness and a reduced lead time. These methods can also be applied to other companies with similar changeover problems.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

The purpose of this research is to investigate the issue of changeover times in the industrial manufacturing setting. A changeover is defined as the elapsed time between the last product ("A") leaving the machine until the first good product ("B") comes out. It is desired to reduce this time so that the machines will be free to process more parts (Van Goubergen and Van Landeghem 2002). A changeover includes the run down, set up, and run up of the machine. The set up is defined as the time required to prepare the machine for product "B" and is performed when the machine is not running.

Throughout this thesis, the terms set up reduction and changeover reduction are used interchangeably. However it is important to understand that "set up" refers to the down time of the machine and "changeover" refers to the entire process that is involved with changing from product "A" to product "B".

Set up reduction was founded by the Japanese industrial engineer, Shigeo Shingo, who coined the term Single Minute Exchange of Die, or the SMED methodology. In traditional manufacturing, companies dealt with the issue of long set up times in one of two ways. The first was to introduce commonality to the set ups which allowed the set up process to remain somewhat constant from job to job. The second was to increase lot sizes which decreases the ratio between set up time and the number of parts produced. Shingo found that increasing lot sizes had several disadvantages and thus, it was necessary to reduce the set up time in order to keep lot sizes down.

Over nineteen years, from 1950 to 1969, Shingo developed his methodology through his consulting work for the Japan Management Association (JMA). While working for the JMA he visited several plants and made some astonishing observations. His main conclusion was that set up operations needed to be distinguished as internal or external operations. Internal operations are performed while the machine is running and external ones are performed while the machine is not running. Tasks such as gathering dies, fixtures, jigs and their fastening devices should all be done while the machine is still running. He defined his final methodology through his work with the Toyota Motor Company where he reduced the set up time of a 1,000 ton press from four hours to ninety minutes (Shingo 1985).

Today, the problem of long set up times is no less significant than it was 50 years ago. In fact, the problem is much more apparent. To compete in today's global markets, companies are being forced to look at ways to speed up production and diversify their product lines while still maintaining a short lead time and producing high quality products. In order to reduce costs, companies have been adopting the principles of Toyota's Just-In-Time (JIT) system which strives to reduce inventory and lead time. The main philosophy is to have the right parts at the right time and in the right quantity. If done correctly, this can dramatically reduce the lost investment opportunity that is tied up by inventory sitting in a warehouse.

The challenge becomes creating a robust system that can handle producing products in a short amount of time while still allowing for extreme product diversity. With a JIT system it has become necessary to reduce set up times to allow for product diversity and low inventory levels. The definition of a set up implies that a set up is essentially lost time, where the company is not producing goods and is not making money. Logically, it is necessary to reduce this time as much as possible in order to reduce the down time of the machine to be as short as possible. Set up reduction strives to do just that; reduce the down time of the machine by minimizing the time required to switch from product “A” to product “B”.

Changeover reduction is directly related to a manufacturing system known as lean manufacturing. Lean manufacturing is also known as the Toyota Production System (TPS) and is designed to eliminate waste in the manufacturing environment (Monden 1998), (Liker 2004), (Womack, Jones and Roos 1990). One way of doing this is by distinguishing between value adding and non-value adding processes in order to make attempts to reduce or eliminate non-value adding processes. A value adding process is defined as a process that adds value in the product as seen in the eyes of the customer. Conversely, a non-value adding process is a process that does not add value to the product. Examples of value adding processes include casting, drilling, assembly, stamping, and anything that alters the product in a way that adds value to the product. Examples of non-value adding activities include material handling, inspecting and storage. Logically, a changeover also falls into the category of a non-value adding activity, and therefore attempts must be made to eliminate or reduce changeover times.

Now that the general idea of set up and its necessity is understood, it is important to find methods to improve upon set ups for real world applications. One method that has been researched quite extensively is that of scheduling jobs in ways to eliminate the changeover itself. If the entirety of the changeover cannot be eliminated then perhaps specific elements of the changeover can be eliminated. If for instance, an external operation is eliminated then this gives the operator more time to perform other tasks.

When creating a schedule it is desirable to reduce lead times, reduce inventory rates, reduce work in progress (WIP), maximize the utilization of resources, and most importantly, meet customer demand. The problem is that these goals directly conflict each other. For example, if utilization of resources is maximized then there may be too much WIP in the system. If lead time is minimized then the inventory rates may have to be increased. These issues coupled with low volume and high product variety makes the issue of scheduling a more difficult task.

Changeovers have a direct tie to the outcomes of an effective schedule; therefore, it will be necessary to consider the two while addressing the issue of changeover reduction. First, consider the issue of reducing inventories which has a direct effect on lead time. In order to reduce inventories, it becomes necessary to decrease the run size which, in turn, requires more changeovers. This increases the lead time of the product because more changeovers are being performed throughout the day. Second, because it is desirable to maximize the utilization of resources, it is also desirable to create a schedule that will reduce the number of changeovers that must take place throughout the day.

The research for this thesis was focused on three different strategies to reduce changeover times. The first was concerned with using the SMED methodology to improve changeover times. The second area of research looked at scheduling jobs so that all of the components that are needed for a particular product are processed during the same time period. The last area of research, involved determining a schedule that placed jobs that share similar tools and fixtures next to each other on the schedule. This reduced the tool and fixture changeover times for the selected set of jobs.

1.1 Background

The bulk of the research for this thesis was conducted at a company that manufactures industrial products that are used in various settings including food manufacturing, construction, and transportation. The manufacturing floor utilizes a process layout that consists of five primary areas, namely welding, machining, assembly, paint, and shipping. The machine shop consists of five horizontal and six vertical CNC machines which all require set ups for each new job.

The bill of material for each product exists in a Material Requirements Planning (MRP) system and components that need machining operations are routed to the machine shop. All of the parts that are machined are classified as “make” items. These parts will start out as raw castings that have been cast at an outside company or raw materials in the form of metal bars and rods. Raw materials are sent to the machine shop as they are called upon by the schedule. The shop has many stations including a saw, horizontal CNC machines, vertical CNC milling machine, and a leading station. Not all of the parts will visit all of the stations; however, they all follow the same order, as listed. Once the parts are machined they are delivered to the assembly stations where they are used as needed. Once the assemblies are finished they are painted and then packaged to get ready for shipping.

Even though this company has many kinds of changeovers at all of the manufacturing areas, this research will only be concerned with reducing the changeover times on the vertical CNC machines. These machines utilize pallet changers that improve throughput dramatically but also make scheduling a far more complicated task. A pallet changing vertical CNC machine consists of two pallets, one that is located under the cutter head and a second that is located on the side of the machine. Parts are attached to the fixture on pallet 1 and are then machined according to the CNC program. While the parts on pallet 1 are being machined the finished parts on pallet 2 are removed and new raw materials are attached to the fixture. This means that there are two different jobs that are set up to run on the machine during the same time period. It is important to note that most changeovers will go from jobs “A” and “B” to jobs “C” and “D”. In some cases the changeover will go from job “A” and “B” to jobs “B” and “C”. Examples of both types are analyzed in this research. Also, all jobs have multiple pieces that are machined in one cycle.

Another interesting aspect of the vertical CNC machines is the tool magazine size. On these machines the magazines can each hold up to 12 tools. Since each machine will run two jobs at the same time this means that the total numbers of tools required by both jobs must be less than 12. This creates complex scheduling problems and can raise questions as to whether it is economical or not to buy machines with larger magazine sizes.

In order to hold the work pieces to the pallets they are fastened to fixtures that are manufactured in house. These fixtures are essential to the productivity of the machine shop and great care has gone into utilizing design features that allow for quick changeovers. The fixtures are also designed to reduce the time required to remove finished goods and attach raw materials in between cycles. Since some of the parts require more than one orientation on the machine, the work pieces must be removed from the fixture and reoriented on the fixture in between cycles. To accommodate this problem some of the fixtures are now modular to allow for quick changes between orientations. In this instance modular refers to a plate which holds several work pieces. This plate is detached from one orientation of the fixture and then reattached in the other orientation. Since the plate holds several work pieces it has eliminated the need to remove and then reattach each individual work piece. The fixtures themselves, modular or not, are rather heavy and in most cases are attached to the machine during the changeover process when the machine is not running. If the fixtures can be altered then perhaps the changeover times can be reduced.

Another aspect of manufacturing that affects changeover time is scheduling, and thus it will be necessary to discuss how this company creates their schedules. Most companies develop unique methods for scheduling jobs, and this company is no different. Orders are entered into a local MRP system as they come in from the sales department. A list of products needed for the orders, along with their due dates, is formulated. This produces a list of how many of each component is needed and by what date. Every Friday the scheduler creates a weekly schedule for each assembly worker who attempts to meet the deadlines of the generated list. Next, the scheduler creates a daily schedule for each area of the machine shop. To do so, a kanban system has been implemented to help generate the list. Jobs with close due dates are marked as “rush” and placed at the top of the list. This kanban system is somewhat of a hybrid because only the highly used components utilize the system. For the rest of the parts the quantities are determined through standard forecasting methods.

The kanban system itself is a two bin system that utilizes bins to manage the inventory levels. Each part number has a predetermined quantity that represents half of the maximum inventory that is desired for that part number. Ideally, the system would work as follows; the assembly area has two bins filled with a particular part. When the first bin is emptied, it is removed from the assembly area and brought back to the machine shop and placed at the bottom of the pile. While the first bin is waiting to be processed by the machine shop, the assembly worker will pull from the second bin that is still in the assembly area. Once the bin in the machine shop is filled, it is then brought back to the assembly area. If the inventory level (the quantity contained by the two bins) is optimized, then the empty bin will be refilled and returned to the assembly area just as the second bin is emptied.

A problem arises when there is demand spike, allowing the inventory levels to run the risk of becoming too low. However, since this demand spike is generally unpredictable, it will most likely not be noticed until the machine shop is too far behind. At this point, increasing the inventory levels will only mean more work for the machine shop. The only way to increase the machine shop’s throughput is by employing more people, buying more machines, or by waiting for the demand to come down.

To adapt to this problem, the company will take the kanban cards and adjust the quantity to be produced during every scheduling period based on their expert knowledge of the system. Because it is very costly to buy machines or hire more workers, this method of increasing inventory levels has been employed as a temporary fix with the expectations that demand will eventually return to normal. This puts tremendous responsibility on the scheduler to adjust quantity levels appropriately. If the scheduler is successful, the machine shop backlog is minimized and important due dates for products are still met.

After the caveats of the general schedule are understood it is necessary to look at the scheduling process of the machine shop so that their issues can be brought to the surface. Again, since this research is focused on changeover reduction for the vertical machines they will be the focus of discussion. Once the daily schedule is created by the scheduler it is then turned over to the machine shop. The supervisors for the horizontal and vertical machines then create a schedule. When the schedule for the vertical machines is determined many variables must be considered such as set up times, cycle times, lot sizes, job priorities, cycle changeover times, tools required, and pieces per cycle. Because some jobs must go through the horizontal machines first, it is necessary to take that into consideration as well. Due to the nature of the input variables this schedule will most likely change throughout the day.

This schedule is then given to the head operator who works with the supervisor to determine when the changeovers need to be performed to ensure that work on the machines flows properly. The head operator is responsible for the changeovers of all of the machines and also operates a machine when possible.

From initial observations of the company it is clear that the issue of changeover reduction has been addressed before. Several of the operations necessary for the changeover have been moved from internal to external operations. For instance, the tool heights for the next job are all set and prepared while the machine is running the current job. Even though changeover reduction is evident in this company, this research will attempt to further improve upon the changeover processes by analyzing the current changeover methods and by creating new scheduling techniques.

Upon completion of this research it is believed that the company being studied will be able to better improve their changeover times by utilizing the changeover methodology proposed in this thesis. It is also believed that the company will be able to schedule jobs in a manner that will reduce changeover times in their machine shop. The methods proposed in this work can also be applied to other companies that utilize pallet changers and are experiencing similar scheduling problems and long changeover times.

1.2 Definitions

Most of the relevant definitions used in the literature are clearly defined and used properly, however; some distinct terms are occasionally used interchangeably.

In order to stay consistent and clear throughout this work it is necessary to define the terminology that will be used. This terminology is often used in academic and industrial settings as common diction, however in order to investigate the issues presented in this work it is necessary to identify the differences in order to eliminate confusion in this thesis.

The most common definition of a changeover is defined as "the time that the last product ("A") leaves the machine until good products ("B") are coming out" (Van Goubergen, 2000). It is also important to distinguish between changeover, set up, and run-up time. The first three terms are defined by McIntosh, et al. (1996):

- ***Changeover:*** The complete process of changing between the manufacture of one product to the manufacture of an alternative product – to the point of meeting specified production and quality rates.
- ***Set up period:*** The set up period is the readily defined interval when no manufacturing occurs. This time is directly analogous to internal time and should not be confused with the time required to adjust the machine for production.
- ***Run-up time:*** The run-up period starts when production is commenced again, and continues until consistent output at full capacity occurs. It is often difficult to

determine the point at which run-up ends and production begins since performance is still varying at this time.

- ***Cycle (or Batch) Changeover:*** The time required to remove the finished goods from the machine and affix the raw materials to the machine. On the vertical CNC machines the batch size will be determined by how many parts fit on the fixture.
- ***Product:*** A finished good as seen by the end user.
- ***Component:*** Parts that make up a product.
- ***Job:*** The process that involves manufacturing a component so that it can be used in a downstream station.
- ***Part Number:*** The number that designates an item to a particular component.
- ***Work Piece:*** An item that is being worked on in a machine.
- ***Unit:*** Used to refer to the quantity of a particular product. For example, "the machine shop produced enough parts to build 30 units of a particular product".
- ***Tools:*** In this context, a tool refers to the tools that are used to machine the pieces in the CNC machine.
- ***Orientations:*** In some cases the pieces on a fixture need to be moved to another orientation in order for all of the machining processes to be completed. A job that requires multiple orientations requires the operator to detach the partially finished pieces and reattach them in a different orientation on the fixture.

1.3 Problem Definitions

Three distinct problems were observed at the company being studied and their proposed solutions were studied in the research.

1.3.1 Initial Observations

Problem: The time that is devoted to changeovers it too long. Since the company has hundreds of components that need to be machined on the vertical CNC machines there is a lot of time that is devoted to changeovers.

Solution: Use the SMED methodology to indentify and convert internal operations to external operations. A changeover methodology is to be developed that will maximize the operators time during the changeover. The proposed changeover methodology also establishes a standard work sheet to be used by the operators.

1.3.2 Method I: Scheduling Jobs in Pairs

Problem: Components for a particular product are not machined at the same time. This causes two distinct problems. First, since some of the components are used for multiple products the quantity of component “A” can get used up while component “B” is on order. Therefore when the machine shop finishes component “B”, component “A” is now out of stock.

Second, the jobs that are being set up on CNC machines with pallet changers are being set up for two jobs. This means that each job is essentially waiting for the other during the changeover process. If the changeover time is looked at from a product stand point then half of the changeover procedure is used on a part that will not be used in the same product. Therefore the changeover time for the product is dramatically increased.

Solution: Components for a particular unit need to be married together so that component "A" and component "B" are made in the same time period, on the same machine. Component "A" will be on table 1 and component "B" will be on table 2.

In addressing the first problem, it is not efficient to machine a component if it is only going to wait in the assembly area for other components. If the components are made on the same machine then they will arrive at the assembly area at the same time. This will also solve many scheduling issues since there will be no question as to which job needs to be paired with which. This means that the components in the assembly area will need to be organized by product so that when the kanban bins are emptied they will all be empty at the same time. If one component is used for two products then there will be two bins; one for each product.

The proposed solution will also reduce the overall changeover time for the product. Essentially the components will get to the assembly area faster because the components will not spend as much time waiting for changeovers in the machine shop. Since two jobs for the same product will be set up on the same machine they will not be "waiting" for jobs that pertain to other products.

1.3.3 Method II: Using Group Technology to Group Jobs According to Tool Usage

Problem: The vertical CNC machines are limited by the number of tools that they can hold (12 tools per machine). This means that after each job the old tools need to be removed and the new ones need to be inserted. Also, the fixtures for each job need to be changed during each changeover. These two activities take up valuable internal time.

Solution: Jobs which require similar tools and fixtures should be placed next to each other on the schedule. This will reduce the tool and fixture changeover times because fewer tool and fixture changeovers will be necessary. The rank order clustering algorithm is used to group together jobs that share the same tools and fixtures.

1.4 Chapter Summary

The issue of long changeover times is a problem for today's manufacturers and needs to be addressed in order to reduce lead times. The company being studied in this research is no exception to this problem and in order to improve lead times it will be necessary to critically analyze and improve upon their changeover methodologies.

Chapter 2 of this thesis will review the relevant literature. Chapter 3 will apply the SMED methodology to the current changeover process at the company. Chapter 4 will discuss the implication of permanently pairing jobs so that the components of a product will reach the assembly area within the same time period. Lastly, Chapter 5 will demonstrate how group technology can be used to arrange the production schedule in a way that will reduce changeover times.

CHAPTER 2 - LITERATURE REVIEW

The literature reviewed in this chapter provides an overview of the changeover reduction process, how it is implemented, and the benefits of changeover reduction. The changeover methods discussed here will be implemented in chapter 3 and chapter 4. This chapter also outlines group technology and the rank order clustering algorithm which will be used extensively in chapter 5. Finally, this chapter discusses the relevant literature regarding standard work, which will be implemented in chapter 3.

2.1 Why Single Minute Exchange of Die (SMED)?

SMED was initially developed by Shigeo Shingo in the late 1950's. Through his work with Toyota and several other manufacturing companies he was able to develop the Single Minute Exchange of Dies, or the SMED methodology (Shingo, 1985). To understand the importance of the SMED system it is first necessary to understand why it is needed and how it effects several aspects of manufacturing.

In traditional manufacturing the economic ordering quantity (EOQ) is a rational way to determine the optimal order quantity of an item and thus determine the inventory levels of the item. As the lot size increases the overall set up time will decrease since fewer set ups will be required, however with larger lot sizes, larger holding costs will ensue. Therefore, finding the intersection of the two lines shown in Figure 1 will logically, and correctly, determine the most economical ordering quantity. The EOQ was first published by Ford W. Harris in the article How Many Parts to Make (Harris 1913).

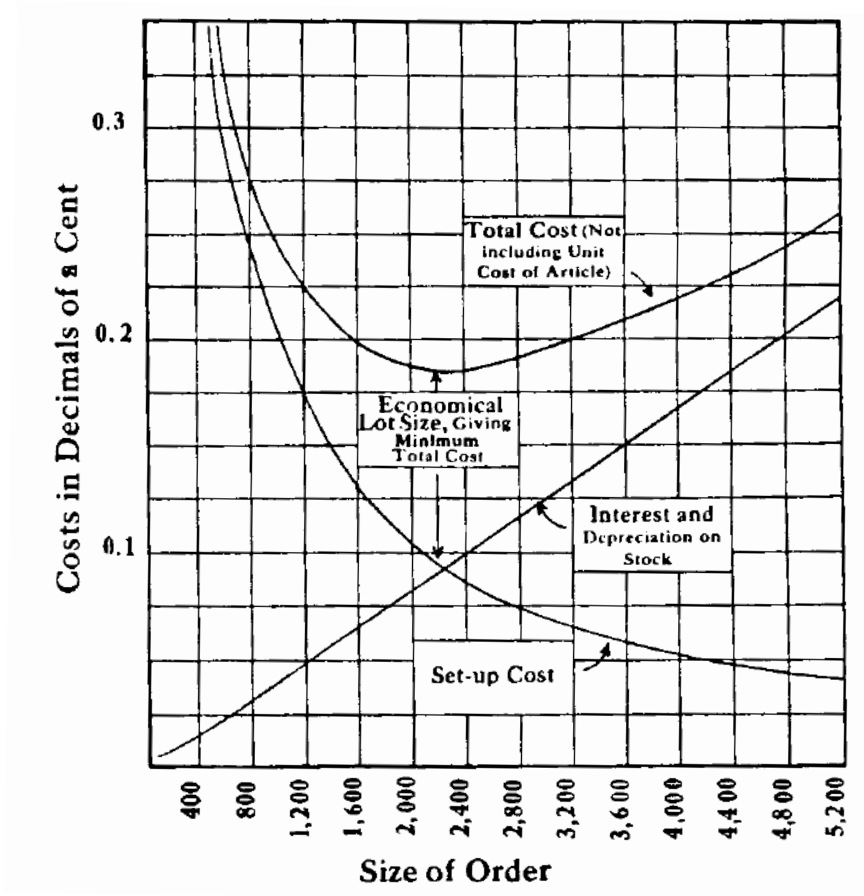

Figure 1: Economic order quantity (Harris 1913)

The Economic Order Quantity is calculated for every part that needs to be ordered in a factory. Figure 1 shows an example of a part that has a monthly demand of 1,000 units, a set up cost of 2 dollars per unit, a unit cost of ten cents, and an interest rate of 10%. This yields an EOQ of 2,190 units. The set up cost is taken as a fixed variable and it decreases exponentially with larger lot sizes. The interest line, or holding cost, is the interest rate times the cost per unit part. The total cost is found by summing the two costs, and from this the EOQ can be found at the minimum of the total cost; or at the intersection of the interest rate and the set up cost. Clearly, as the lot size increases then the negative effects of a set up decrease, but the holding cost of the lot size increases. Equation 2.1 calculates the economic order quantity given several input variables.

$$\boldsymbol{X} = \sqrt{\frac{\boldsymbol{24TMS}}{\boldsymbol{IC}}} \qquad \textbf{(2.1)}$$

Where,

X = Economic order quantity,

M = Monthly demand,

S = Set up cost,

I = Interest rate (holding cost),

C = Cost per unit part,

T = Manufacturing interval in months.

When Harris developed the EOQ model in 1913 the set up cost was taken as a fixed variable, much like one would consider the overhead of a plant as a fixed cost. However, if the set up time is reduced then a reduction in the set up cost will be seen. Reducing this set up time is the primary focus of set up reduction. A reduction in set up times will lower the set up reduction cost line, and therefore, lower the EOQ level.

By studying the fundamental formula for order quantities, it can be seen that there is a gap in the traditional ordering policies for manufacturers. Instead of looking at the inputs to the EOQ as fixed variables, managers need to look at ways to improve their manufacturing processes in order to improve upon these variables. By increasing manufacturing times and decreasing the time spent on set ups, the productivity of a plant can be significantly increased. This "missing link" between the EOQ and set up times is exactly what set up reduction aims to do.

It is also well documented that short set up times provide many advantages to manufacturers (Rother and Shook 2003), (Mileham, Culley and McIntosh, et al. 1997), (McIntosh, et al. 2001) (Nakajima 1988). Furthermore, Van Goubergen (2000) has defined three key reasons for short set up times (Van Goubergen 2000).

- **Flexibility and Inventory Reduction**

  It is understood throughout industry that in order to get ahead of the competition, companies need to manufacture more product types in a shorter amount of time. In order to fulfill these customer demands there are two approaches that can be taken; to either have high inventory levels so the company will not run out of products or to reduce the set up times so that a higher range of jobs can be produced in the same amount of time. The EOQ formula shows that the latter method, which shortens lead time, is more desirable.

- **Bottleneck Capacities**

  Every manufacturing plant has at least one bottleneck, and as a bottleneck prevents factories from meeting their demand a decision to buy more machines or alter the manufacturing process has to be made. A lean manufacturer would instinctually look to the process in order to solve the problem. In this case a lean manufacturer would look to reduce set up times. Since reducing set ups will improve production time, it will therefore improve your production capacity. Consequently, Implementing SMED, if done correctly, can eliminate the need for a new machine.

- **Cost Minimization**

  If the cost to manufacture a product is reduced then profit margins will increase. In other words, if the time used for set ups is reduced then costs will go down. Another way to look at this is through a metric called the Overall Equipment Effectiveness (OEE). If the set up time decreases then the effectiveness of a machine will increase and therefore costs will also decrease (Nakajima 1988).

Spence and Porteus (1987) developed a model that optimizes set up time and overtime to increase effective capacity (Spence and Porteus 1987). This article proves that by including overtime and set up reduction in the lot sizing models then the total cost per week to create a part will decrease. Given the cost to implement a set up reduction initiative, an optimal reduction target can be found. And given the overtime cost relative to the set up reduction cost, the optimal overtime hours can also be found.

Olhager and Rapp (1991) found that the inventory turnover rate will increase as set up times decrease (Olhager and Rapp 1991). It is also shown that a reduction in set up times can reduce the lot size, or Finished Goods Inventory (FGI), and the queueing time or, Work In Process (WIP).

Cakmakci (2008) proves that SMED improves both changeover performance and equipment/die design and development (Cakmakci 2008). It has also been proven that set up reduction is necessary in pharmaceutical manufacturing as well (Gilmore and Smith 1996).

2.2 What is SMED?

The phrase single minute exchange of dies originated from Shigeo Shingo who developed the SMED system during the 1950’s and 1960’s (Shingo 1985). He noticed that the process of exchanging dies for large presses took hours when it could be done in minutes. His goal was to reduce the set up time of the presses from hours to 1 minute. In some cases he was able to reduce the set up time to under a minute but in most cases the set up time was reduced to less than 10 minutes.

Table 1 shows a list of results for different presses and companies where Shingo was able to perform SMED. The data shows an average of 94.4% reduction in set up time (Shingo 1985).

No.	Company	Capacity (in tons)	Before Improvement	After Improvement	1/n
Presses (single-shot dies)					
1	K Auto	500 t-3 machines	1 hr 30 min	4 min 51 sec	1/19
2	S Auto	300 t-3 machines	1 hr 40 min	7 min 36 sec	1/13
3	D Auto	150 t	1 hr 30 min	8 min 24 sec	1/11
4	M Electric	"	2 hr 10 min	7 min 25 sec	1/18
5	S Electric	"	1 hr 20 min	5 min 45 sec	1/14
6	M Industries	"	1 hr 30 min	6 min 36 sec	1/14
7	A Auto Body	"	1 hr 40 min	7 min 46 sec	1/13
8	K Industries	100 t	1 hr 30 min	3 min 20 sec	1/27
9	S Metals	"	40 min	2 min 26 sec	1/16
10	A Steel	"	30 min	2 min 41 sec	1/11
11	K Press	"	40 min	2 min 48 sec	1/14
12	M Metals	"	1 hr 30 min	5 min 30 sec	1/16
13	K Metals	"	1 hr 10 min	4 min 33 sec	1/15
14	T Manufacturing (dies for springs)	80 t	4 hr 0 min	4 min 18 sec	1/56
15	M Ironworks	"	50 min	3 min 16 sec	1/15
16	H Engineering	50 t	40 min	2 min 40 sec	1/15
17	M Electric	"	40 min	1 min 30 sec	1/27
18	M Electric	"	50 min	2 min 45 sec	1/18
19	H Press	30 t	50 min	48 sec	1/63
20	K Metals	"	40 min	2 min 40 sec	1/15
21	Y Industries	"	30 min	2 min 27 sec	1/12
22	I Metals (multiple dies)	"	50 min	2 min 48 sec	1/18
23	S Industries (progressive dies)	150 t	1 hr 40 min	4 min 36 sec	1/22
24	K Metals	100 t	1 hr 50 min	6 min 36 sec	1/17
25	M Electric	100 t	1 hr 30 min	6 min 28 sec	1/14
				Average	1/18

Table 1: Time reductions achieved by applying the SMED methodology (Shingo 1985)

Shingo developed the SMED methodology that identifies which changeover operations are accomplished when the machine is running and when the machine is not running. The main goal of the methodology is to maximize the number of operations that are done when the machine is still running, and thus producing saleable goods. The methodology also strives to minimize the time required to complete all of the changeover tasks.

A key reason for slow set up times in the past stems from the misunderstanding of internal and external operations. It may seem obvious that it is optimal to perform as many of the set up tasks as possible while the machine is running; "Nonetheless, it is absolutely astounding to observe how often this is not the case" (Shingo 1985). The definitions for internal operations, external operations, and changeover activities are defined as follows (Shingo 1985):

- **Internal Operations**

These are tasks that must be performed when the machine is not running and is not producing parts. It is important to understand that internal time is also considered as the time where run down and run up of the machine occurs. Even though there are parts being produced during this time the line is still not fully operational and is therefore considered as internal time.

- **External Operations**

These are tasks that can be performed while the machine is running and producing parts. These tasks can be performed before or after the machine is shut down for the set up.

- **Changeover Activities**

The changeover activities consist of all the tasks necessary to complete a changeover. This includes both internal and external tasks.

The main functions of any set up can be defined by four basic procedures (Shingo 1985).

- *Preparation, after process adjustment, checking of materials, tools, etc.*

  This step involves locating all of the parts and tools and ensuring that they are in the right position. It also includes putting tools away after the set up has been finished.

- *Mounting and removing blades, tools, parts, etc.*

  This includes removing old parts and tools after the previous operations and affixing the new tools for the next operation.

- *Measurements, settings and calibrations.*

  This step involves all of the calibrating that is necessary for the production operation that is about to be performed.

- *Trial runs and adjustments.*

  This is where adjustments are made after a test piece is made. If the measurements and calibrations are more accurate then this time will be reduced or eliminated.

The three stages of set up reduction, as defined by Shigeo Shingo, aim to convert the internal operations to external operations. These stages are defined as follows (Shingo 1985):

Stage 1: Separating Internal and External Set up

In this stage, the set up reduction team looks at every process and determines whether or not each process is being performed internally or externally. If steps are not clearly in one category or the next, then adjustments are made to make them separable.

Stage 2: Converting Internal to External

This stage involves analyzing each step and converting the internal steps to external ones. This is where the creativity of the operators and employees comes into play, in order to generate methods to convert internal processes to external processes.

Stage 3: Streamlining All Aspects of the Operation

In most cases it is necessary to streamline the operations so that the set up can be reduced to the single minute range. In this stage it is necessary to analyze each individual operation to determine ways in which they can each be performed in less time.

As with all lean principles, the main goal is to eliminate waste which will ultimately improve the system's performance. Therefore it is necessary to target the most common types of waste that are seen during changeovers (Sekine and Arai 1992).

The three main types of waste are as follows:

- ***Set up Waste*** is associated with the time spent searching, finding, selecting, lining up, and transporting. The easiest way to eliminate this waste is to simply ask if this operation is necessary, and can the operation be done before the machine is stopped. Organizing all of the tools, settings, and necessary items for the set up in one location is a good way to reduce set up waste.

- ***Replacement Waste*** is associated with removing and fastening bolts. Most of the time spent in attaching or removing a die is consumed in securing the dies to the machine and in the majority of cases it is possible to reduce this time.
- ***Adjustment Waste*** is most commonly found when operators do not adhere to the standards set for producing the new part. If the operator uses an instrument that is more precise than needed then a considerable amount of time will be lost due to unnecessary adjustments.

2.3 Changeover Reduction Methods

There have been two major approaches that have been developed to reduce changeovers. The first is known as the ‘modification by design and methodology’ approach and the second is known as the ‘design of a new system’ approach (Mileham, et al. 1998).

The first approach changes the existing system by modifying the design of the changeover system and the methodologies used to accomplish the changeover. For example, a methodology based improvement would consist of improving the efficiency of the methods by which the fixtures and dies are attained for the set up. While a design based improvement would consist of redesigning the fixtures and dies so that they can be set up faster.

To give an example, suppose a company is making an item that requires milling a plastic part and a steel part on a vertical CNC machine, both of which require different fixtures. When the company needs to switch from the plastic parts to the steel parts they will need to collect the raw steel for the parts, the tools for changing out the fixture, and the new tools that need to be installed on the machine. A methodology based improvement would consist of developing a set up cart that contains all the necessary tools and fixtures. A design based improvement would consist of using ¼ turn bolts instead of full length bolts.

The second approach, designing a new system, consists of completely overhauling the existing system. This also involves redesigning the capital equipment. For example, suppose a company uses a 10 ton press to manufacture a variety of parts.

Designing a new system would involve redesigning or replacing the 10 ton press in order to have equipment that requires less changeover times.

It is understood that designing a new system would be more time consuming and expensive but a much larger reduction in changeover time can be achieved. Conversely, the modification by design and methodology approach will be less expensive but the overall reduction in changeover time will be less. Researchers have also noted that sustainability is more difficult when using the modification method (Culley, et al. 2003).

Figure 2 shows the two aforementioned approaches, as a function of changeover time and cost. The lower two curves of Figure 2 represent the two strategies that can be implemented through the modification by design and methodology approach. It is clear that the modification by methodology approach cannot reduce changeover times as much as the other methods; however, the cost is much lower. There is also a limit to the modification by design and methodology approach but it will produce more time reductions at a greater cost. The upper curve clearly demonstrates that designing a new system has the highest opportunity for changeover reduction; however, the associated cost is significantly higher.

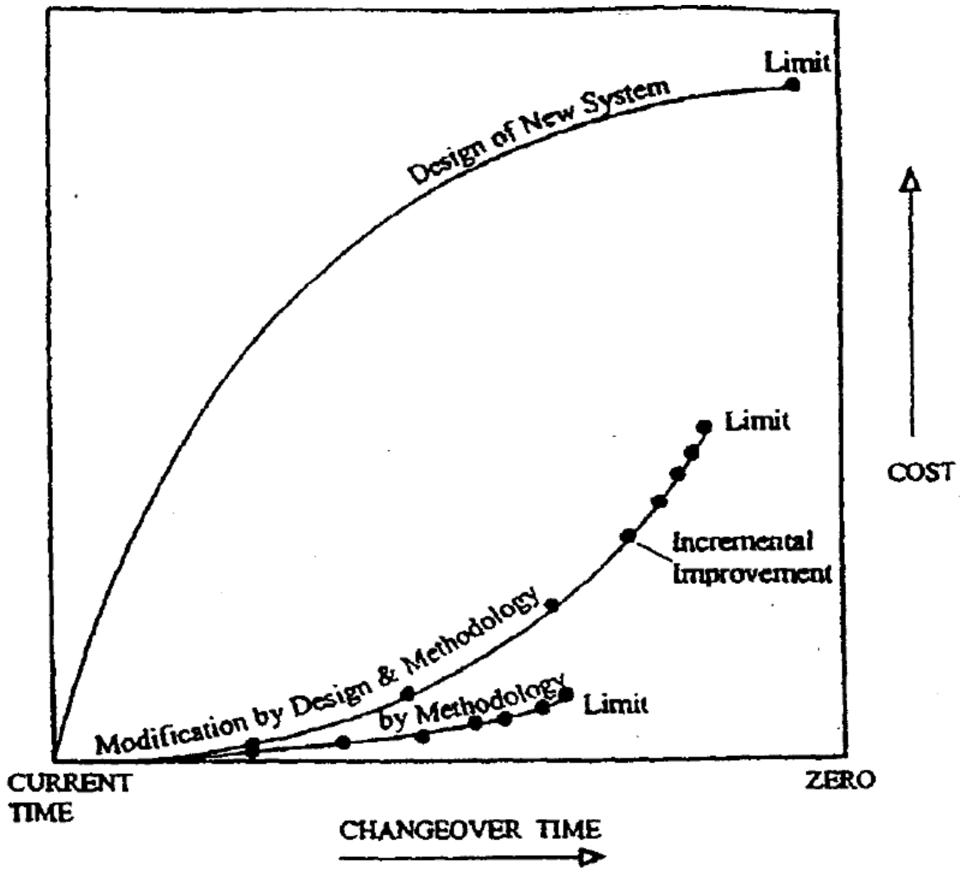

Figure 2: Limits and costs of changeover improvement strategies (Mileham, et al. 1998)

When defining the two strategies for the changeover reduction problem it becomes obvious that while the design of a new system approach can produce better results, the bulk of the literature only investigates the modification approach. In fact, it is difficult to find a concise and common definition that defines the design of a new system approach. The definition can be interpreted as "a completely new system that strives for automation in set ups", however, this approach is beyond the scope of this thesis.

2.4 Guidelines and Rules for Changeover Reduction

Since it has been difficult for researchers to study the ‘design of a new system’ approach, a lot of focus has been given towards establishing rules and guidelines for improving the modification approach (Mileham, et al. 1998), (Van Goubergen and Van Landeghem 2002), (Reik, et al. 2006), (Van Goubergen and Van Landeeghem 2001).

The first set of rules were constructed by Mileham et al. (1998) who developed six generic sets of rules that can be applied to the design of a new or existing system (Mileham, et al. 1998). Mileham’s group was the first to coin the phrase “design for changeover” (DFC) which lays out the groundwork for a DFX method that can be applied to changeovers. Design for X has been well utilized in many areas of product development such as ergonomics, manufacture and assembly, and disassembly. Design for manufacture and assembly (DFMA) utilizes a method that assesses the manufacturability of a product and implements the results during the design phase of the product (Boothroyd, Dewhurst and Knight 2002). The same theory can be applied to changeover reduction by analyzing each and every step of the set up in order to identify any wasteful steps. Once the changeover has been analyzed, the process can be improved by applying the rules presented in Table 2 (Mileham, et al. 1998).

1. Light weighting	- use lighter materials. - use less material.
2. Simplification	- reduce the number of mechanisms. - eliminate the need to remove parts which are not part of the changeover. - eliminate the need to remove complete assemblies. - eliminate pipe connections or use quick release couplings - reduce the number of tools required. - reduce the total number of components in a tool. - simplify control procedures such as timing diagrams. - use short power drive connections.
3. Standardisation	- use the same size shut heights for presses. - use the same size securing bolts. - use the same types of electric motors
4. Securing	- use the minimum number of fasteners consistent with strength. - eliminate manually operated clamps. - use 1/4 turn devices.
5. Location and Adjustment	- eliminate on-machine adjustments. - provide intelligent adjustment and monitoring. - eliminate the use of spacers and shims. - provide dead stop positioning.
6. Handling	- eliminate the need for or ensuring easy cleaning/purging. - eliminate the need to handle hot items. - eliminate the need to handle awkward items. - provide power aids. - provide remote actuation. - ensure easy delivery of the tool to the machine - provide good access.

Table 2: Design for changeover rules (Mileham, et al. 1998)

These rules have countless examples of methods that can be used to make the set up process easier and more efficient (Shingo 1985). When fixtures are used to hold parts in CNC machines they are often made from steel and can weigh quite a bit. If the fixtures were lighter or broken down into two fixtures then the handling would be easier and this may make it possible for the operator to carry the fixture instead of needing a cart or forklift. Simplifying tasks is also a great way to save time. An example is to simplify the process by which the CNC programs are loaded onto a machine. Standardizing the bolt size so that fixtures and parts are bolted together with the same size bolts is another example of simplification. Figure 3 shows many examples of quick fastening devices that can also be used to reduce the time it takes to secure an item. Securing many items to a fixture externally can save a lot of time since the machine can be running during this time. These are just a few examples of how applying the rules in Table 2 can help the designer furnish methods to improve the changeover process.

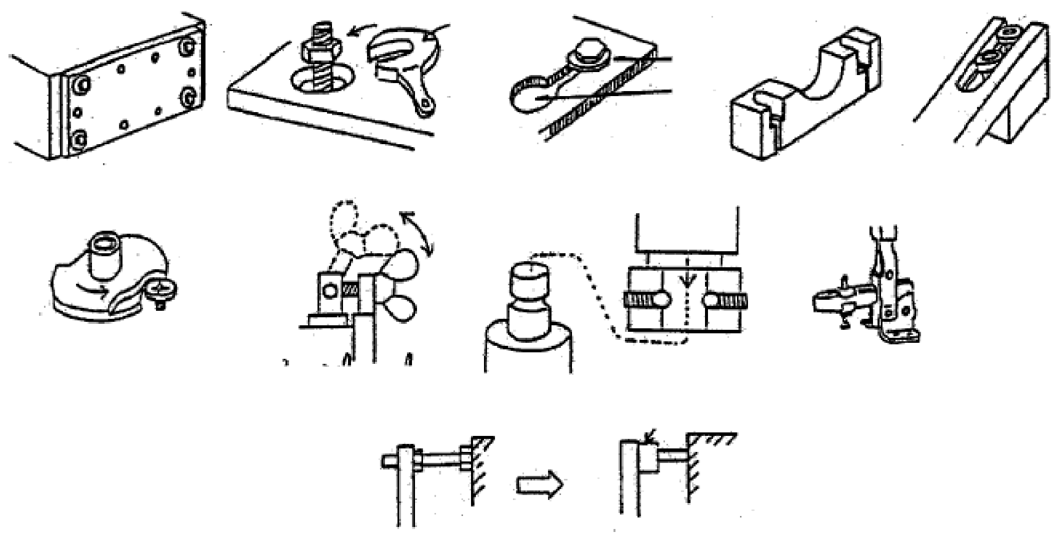

Figure 3: Quick fixtures (Shingo 1985)

Monden (1998) gives a practical procedure for improving changeover time in chapter 9 of the book "The Toyota Production System" (Monden 1998). It is suggested that the existing process is first analyzed by videotaping the process and then conducting time and motion studies. Once this is complete there is a four step process that needs to be performed in order to reach the goal of zero minute changeover time. The first step is to differentiate between the internal and external set up operations. The second step is to continuously improve the operations to reduce the internal set up time. Step three is to improve the equipment so the internal time can be minimized. And the last step is strive for zero set ups. While this last step is not always possible, the design team can still look for ways to redesign the parts or eliminate the need for the changeover.

Van Goubergen et al. (2002) has developed a strategy that specifically alters the rules listed in Table 2 that were developed by Mileham et al. (1998). The adapted design rules can be found in Table 3. The authors of Table 3 have taken Table 2 and added several rules and adapted the rules appearing in italics.

2. Simplification	
2.3	*Remove complete assemblies/modules that can be prepared off-line instead of removing and mounting several smaller parts on-line*
2.9	Use Poka Yoke systems (mistake-proof systems)
2.10	If a part that needs to be exchanged has only 2 sizes, put one fixed on the machine
3. Standardization	
3.4	Design universal machine parts that do not need to be exchanged
4. Securing	
4.2	*Use manual clamps as a cheap and fast alternative for bolts and screws*
4.4	Use quick fixtures
4.5	Use hydraulic, pneumatic or electromagnetic fixtures
5. Location and adjustment	
5.5	Provide positioning using centring pins—holes
5.6	Use discrete positioning of parts in stead of continuous
5.7	Settings 'right from the first time'
5.7.1	Identify all parameters that influence the process
5.7.2	Determine the correct setting values for all parameters, per type of product – these values need to be written in the set-up instruction
5.7.3	Install means to effectively set these values
5.8	Enable off-line checking of products by improving the quality of setting activities
5.9	Provide measuring devices, preferably using digital displays
5.10	Use stepping motors for accurate setting
5.11	Every knob/wheel needs to have a measuring scale
5.12	If possible, use 1 setting parameter per product property/specification
5.13	Provide re-adjusting procedures that give a direct link between an observed fault on the product and the parameter that has to be re-adjusted, together with how much it needs to be re-adjusted
6. Handling—movements	
6.8	Appropriate placement of buttons and control panels to avoid additional/unnecessary movements
7. Off-line activities	
7.1	Enable off-line mounting/removing of aids, supports and fixtures
7.2	Enable off-line loading of numerical control data for PLC, CNC (before set-up)
8. Machine lines	
8.1	Decouple the drive of every station to enable set-up activities on a single station while the last/first products run through the other workstations

Table 3: Adapted and additional design rules (Van Goubergen and Van Landeghem 2002)

The first rule that was changed was rule 2.3. In Table 2 the rules states that the designer should eliminate the need to remove complete assemblies. This rule was modified in Table 3 to state that the operator should remove the assemblies that can be completed off-line instead of assembling multiple parts on-line. For example, a company that machines small metal parts for electric motors will machine several parts at a time. Instead of loading all of the parts onto the two-piece jig while the jig is in the machine they will remove the entire assembly and load the pieces into the jig off line. They will then install the jig into the machine with the help of quick fastening devices to align the jig to the machine.

Another interesting application is that of rule 2.10 which states “If a part that needs to be exchanged has only 2 sizes, put one fixed on the machine”. If a company manufactures two kinds of metal parts in the same press then the die for the smaller of the two parts can be left in the machine. When it comes time to make the larger part then the larger die can be placed over the first die and held in place by a nesting device.

Van Goubergen et al. (2002) and Mileham et al. (1998) seem to disagree on the use of manual clamps and automatic clamps. Manual clamps have the advantage in that they are cheaper and easier to install. However, automatic clamps do have their advantages since they can quickly clamp to a more accurate torque specification. The manual clamps have a wide range of applications that, with a little creativity, can be used in areas where some automatic clamps cannot.

The most comprehensive list of rules and guidelines that can be followed to improve changeover performance was found in Reik, et al. (2006) where the authors present nine steps that give an outline of the DFC process. The nine steps, divided into two stages, are shown in Table 4.

These rules were designed to help the Original Equipment Manufacturer (OEM) designer but can also be used to help the engineers concerned with the existing manufacturing systems. As discussed in Figure 2 there are two general strategies that an engineer can use in order to reduce changeover times. It is interesting to note that the authors and creators of this DFC method, who are the same authors of Figure 2, claim that both systems are very different in nature but the nine steps can be applied to OEMs and the existing systems. It seems as though it is possible to apply the rules for improving changeovers to both methods even though they are intrinsically different.

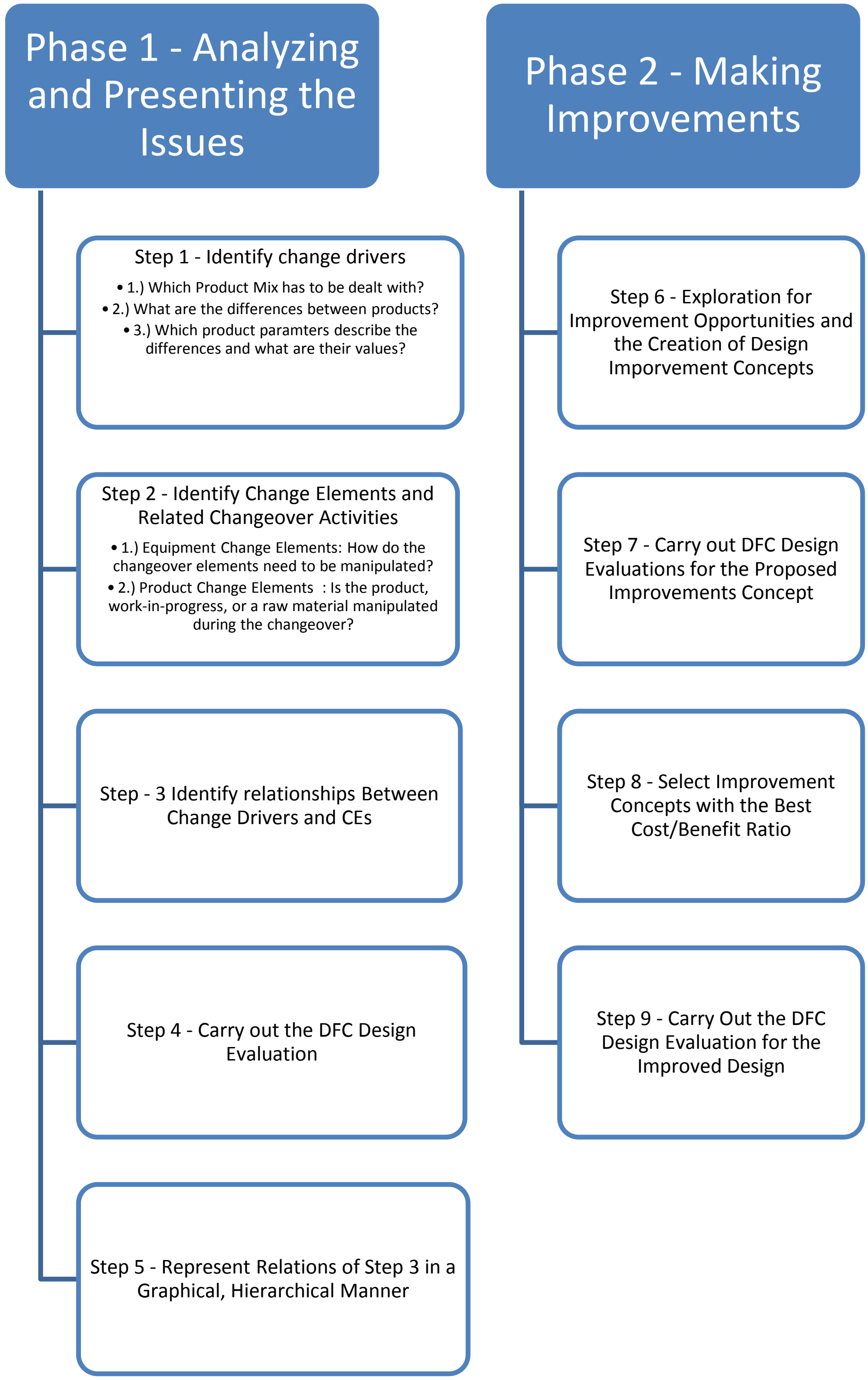

Table 4: The design for changeover methodology (Reik, et al. 2006)

The easiest and most effective way to reduce changeover times is to eliminate the changeover (Reik, et al. 2006). Therefore, it is helpful to identify what drives the need for one product to get changed to the next product. If it is found that such a change is not necessary then the changeover can be eliminated. Next, it is necessary to identify the product parameters of a product which will help show what needs to be changed in the changeovers. Step 2 is to identify a list of change elements and a list of related changeover activities for each element. Step 3 provides a matrix with the interaction between the change drivers and the change elements which shows the effect that each one has on each other. Step 4 is accomplished with the use of the design for changeover evaluation sheet (Reik, et al. 2006, b). This sheet will determine the design efficiency indices. The first is the design efficiency index (Reik, McIntosh, et al. 2006, a):

$$I_{DE} = \frac{necessary\ CE}{all\ CE} 100\% \quad \textbf{(2.2)}$$

The second is the changeover activity index:

$$I_{DE} = \frac{time\ of\ necessary\ changeover\ activities}{time\ of\ all\ changeover\ activities} 100\% \quad \textbf{(2.3)}$$

Where,

I_{DE} = Design Efficiency Index,

CE = Changeover Element.

Step 5 is concerned with creating a change driver flow down tree to visually display the relationships between the change drivers and the change elements. An example of a change driver flow-down tree can be seen in Figure 4.

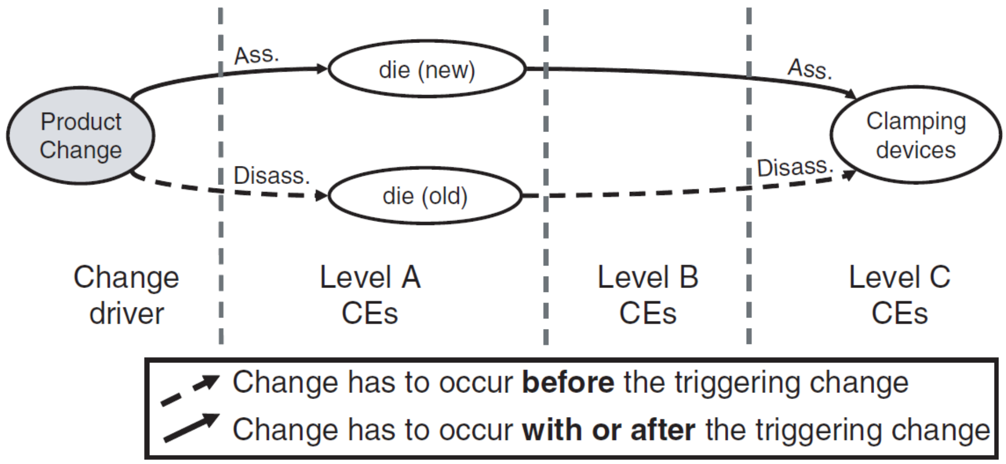

Figure 4: Example of a change driver flow –down tree (Reik, et al. 2006)

In step 6 the designer can use the algorithm in Figure 5 to explore ways to eliminate or alter the change elements in order to find improvement possibilities.

1. Go to Level A in the change driver flow-down generated in step 5.
2. For all CEs on this level, check improvement possibilities:
   - (a) Eliminate CE by:
     - (i) eliminating influence of change drivers or higher level CEs
     - (ii) Grouping CEs into modules with other CEs of same or higher level
   - (b) Reduce effort to change this CE, for example by:
     - (i) Minimizing securing/releasing effort;
     - (ii) eliminating the need for adjustment;
     - (iii) provision of setting, measuring, testing, and controlling devices and procedures;
     - (iv) provision of power tools;
     - (v) use of Poka-Yoke (foolproof design);
     - (vi) weight reduction;
     - (vii) increase of accessibility;
     - (viii) separation of CE into modules to accommodate changes more easily.
   - (c) Enable changing of CE in parallel to others.
3. Go to next level in change driver flow-down and continue with step 2

Figure 5: Step 6 - Algorithm (Reik, et al. 2006)

The next step in Reik's design for changeover methodology is to evaluate all of the improvement concepts in terms of time reduction and cost savings. The last step is to select the improvements with the best cost/benefit ratio.

This process is intended to give a design engineer an overall methodology for what drives the need for set ups, the interaction with the drivers and the elements that need to be changed, and a process to improve the set up. The process uses several methods to analyze the existing system and motivates the designer to evaluate the reason for each element of the changeover. While this method does have concrete methods, it is still fairly abstract as the authors of Reik et al. (2006) are probably trying to cover a wide range of applications. More specific worksheets and methods may also be necessary for different applications, whether they are CNC machines, or 10 ton presses.

Van Goubergen et al. (2001) explains a specific methodology for changeover reduction and gives methods for analyzing the existing system while keeping the scheduling of multiple machines in mind (Van Goubergen and Van Landeeghem 2001). The process looks at utilizing the DFX approach to analyze the existing system and systematically improve the changeover process. The methodology also looks at the problem of having several machines and a limited number of workers. In addition, Van Goubergen et al. (2001) strive to use industrial engineering (IE) approaches to bring the most restraining elements of the changeover to the surface so that they can be analyzed and solutions can be found.

The overall approach presented by (Van Goubergen and Van Landeeghem 2001) can be seen in Figure 6 which can be directly compared to Table 4. The approach below gives a more specific methodology that looks at displaying the problems of the existing system in a visual way through the use of multi-activity diagrams and set up reduction analysis sheets.

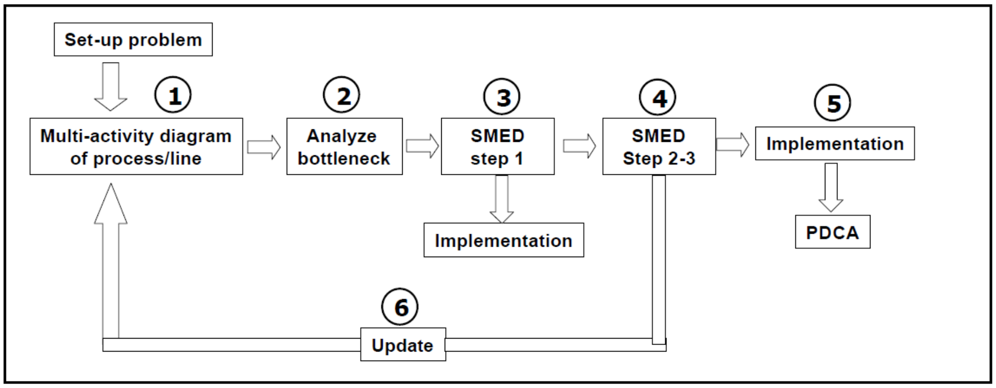

Figure 6: Integrated approach for set up reduction – general overview (Van Goubergen and Van Landeeghem 2001)

The first step is to utilize the multi-activity diagrams for both the machines and the operators. These diagrams are meant to locate the bottleneck in the system by displaying the state each machine and if other operations are forcing them to wait. The multi-activity diagrams can also be used to maximize the operators time.

Step two involves filming the set up process and using the set up reduction analysis sheet to create a time based tally of what is being done and when. This is very comparable to manual assembly and DFMA (Boothroyd, Dewhurst and Knight 2002) where the existing process is analyzed through a time study and then the product is improved upon. Here, the manual assembly operations are comparable to changeover activities and the product is comparable to the set up jigs, fixtures, and processes. After recording the set up times, a Pareto diagram is utilized to show the bottleneck of the system. A routing diagram can also be used to show the walking waste in the system.

The next step is to implement SMED step 1 where internal components are converted to external components. This is where the ideas from Shingo's SMED methodology can be applied and it will also be helpful to use Table 2 and Table 3 to help the designer brainstorm changeover reduction ideas. At this stage it is also important to develop changeover instructions and checklists. Figure 7 shows the process for step 3.

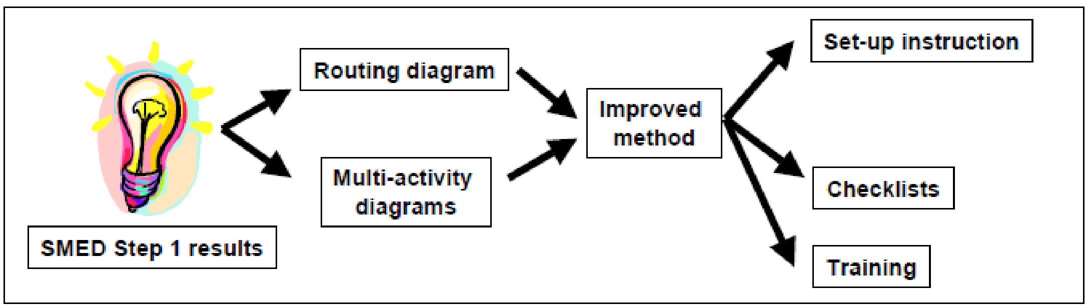

Figure 7: Step 3 – SMED step 1 (Van Goubergen and Van Landeeghem 2001)

Step 4 is to implement SMED step 2 and 3. This is where the Pareto charts and bottleneck analysis are used to show the designer which areas of the changeover process should be the focus. Also, a cost-benefit analysis of each proposed method is done to help decide which methods should the focus. Once the best ideas have been selected it will be necessary to establish an implementation plan for the selected ideas. The process for step 4 is shown in Figure 8 which is essentially the same as the previous step however this step utilizes an implementation plan.

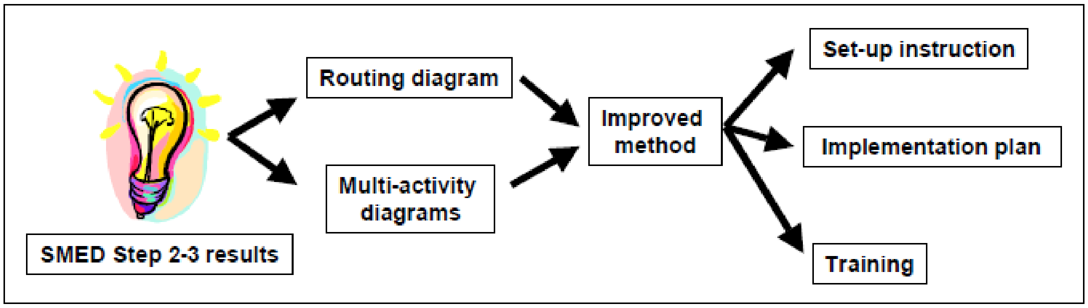

Figure 8: Step 4 – SMED step 2 and 3 (Van Goubergen and Van Landeeghem 2001)

Step 5 is where the plans are implemented and the actual changeover process is altered. The last step is to update and re-determine the bottleneck so that the process can be repeated in order to achieve further reductions. This procedure of re-evaluating the process is known as the Plan-Do-Check-Act (PDCA) cycle that can also be applied to many other areas of the shop floor (Deming 2000).

While the articles discussed in this section address the issue of finding a set of guidelines to assist the user in a changeover reduction project it should also be noted that there are other well established methods that can be used to evaluate and improve a process. A work study is another tool that can assess the existing system by examining human work and systematically investigating all of the factors that affect the efficiency of a process (Kanawaty 1986). Also, time studies have been used for decades in order to discover how long a process takes and what can be done to improve the efficiency of the process (Mundel 1970). These two methods have been studied extensively for years and many aspects of their methods can be applied to the changeover process.

2.5 Group Technology

Group Technology (GT) is a process that groups parts with similar features into families so that their similarities can be utilized during production (Groover 2008). The most formal and accepted definition of group technology is defined as “a manufacturing philosophy that identifies and exploits the underlying sameness of parts and manufacturing processes” (Ham, Htomi and Yoshida 1985).

The main goal of GT is usually to reduce the distance a part must travel on the manufacturing floor. If machines are organized into machine groups, or cells, then lead time and work in progress inventories can be reduced (Groover 2008).

GT is used to convert a process oriented layout to a product oriented layout by grouping machines according to the parts that they process. In order to do this, it is necessary to group jobs into families by classifying them by the manufacturing processes that are used to manufacture the part. Once this is accomplished, then it is possible to convert the floor plan to a product oriented layout.

Once a process is converted to a product oriented layout, then it can be converted to a cellular layout where a family, or product line, is dedicated to a manufacturing cell. A Cellular Manufacturing System (CMS) is defined as “a set of manufacturing and/or assembly cells, each dedicated to the manufacture or assembly of a part family or group of products, respectively” (Irani 1999). Figure 9 visually depicts the differences between product layouts, cellular layouts, and functional (process) layouts.

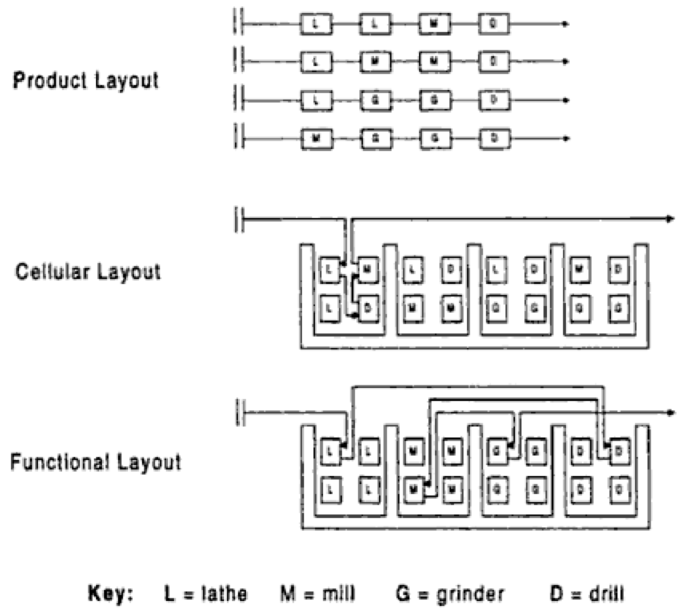

Figure 9: Product, cellular, and functional (process) layouts (Irani 1999)

It has been shown that cellular manufacturing will provide the manufacturer with an advantage if the set up times are long, demand is predictable, the flow of jobs through a manufacturing cell is unidirectional, and move times are long (Morris and Tersine 1990). Cellular manufacturing can increase machine utilization, operator utilization, production rate, and productivity. Cellular manufacturing also reduces WIP inventory, material handling, throughput time, set up time, and cycle time. Figure 10 displays the advantages of cellular manufacturing (Parashar 2009).

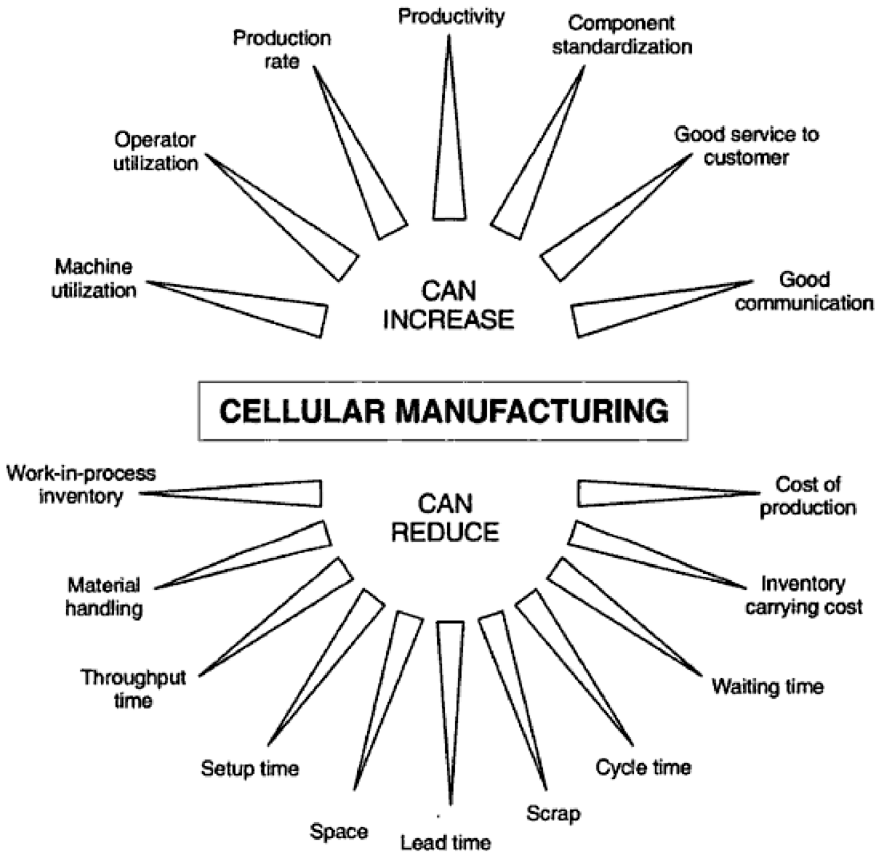

Figure 10: The benefits of cellular manufacturing (Parashar 2009)

According to Hassan (1994) there are three main steps required to develop a GT layout. The first is that the parts need to be classified according to their similarities. Second, the machines and work stations need to be organized within each cell. And lastly, it is necessary to find the configuration of cells on the machine floor. While accomplishing these three steps it is most important to remember that the main goal of group technology is to minimize the transportation cost (Hassan 1994).

One method for classifying the part families is known as production flow analysis (PFA). This method analyses the information that is contained in the process routes of the machines. First, the machines are classified into special, intermediate, common, general, and equipment. The method then counts how many parts are used by each machine. Next, the first two steps are combined to re-sequence the plant list according to the processes route data attained in step 1 and step 2. The method then finds “modules”, or sets of parts, that are based on the machines listed in step 1. Then the method finds a module/machine matrix to find the families. Lastly, the method eliminates any exceptional operations from the families (Burbidge 1996) (Burbidge 1975).

It has been observed by King (1980) that the module/machine matrix needed for the production flow analysis can be found by applying the rank order cluster (ROC) algorithm (King 1980). The algorithm can be used as an alternative to performing a PFA. There are many methods that can be used to formulate the machine/module matrix, such as the direct clustering algorithm, the bond energy algorithm, the modified ROC algorithm, and the occupancy value algorithm (Parashar 2009). The ROC algorithm is the algorithm that will be used in this thesis because it is most applicable to this research.

Using the data from the PFA, the ROC algorithm creates a machine component matrix where the cell entries for all values of i and j are $x_{ij} = 1$ or $x_{ij} = 0$. A cell entry of 1 represents that component j requires machine i and a blank entry represents a 0. The ROC algorithm then arranges a random cluster of components and machines into groups that are arranged along the diagonal of the matrix. When the algorithm is finished it is possible to distinguish groups of machines and components. This algorithm is explained in detail by King (1980). An application and example of the ROC can be found in (Groover 2008) and (Suresh and Kay 1998).

Once GT has been applied to a manufacturing facility it is then necessary to find an appropriate means of scheduling jobs to the manufacturing cells. It has been widely accepted that parts of the same family will share some of the same set up characteristics (Irani 1999). In order to find a schedule that considers set up characteristics, heuristics are often used to find an optimal solution. One type of heuristic is the exhaustive heuristic that processes all of the subfamilies (i.e. part numbers) that belong to the same family before changing over to the next family. A non-exhaustive heuristic considers the changeover characteristics of each subfamily. For instance, some subfamilies may use the same milling tools and would therefore be scheduled back to back in order to minimize tool changeovers. Non-exhaustive heuristics are known as sequence dependent heuristics because the subfamily is dependent upon the one it follows on the schedule. Heuristics of this nature will not only reduce the set up times in between subfamilies, but will also reduce the total number of set ups (Irani 1999).

Wemmerlov (1992) has concluded that scheduling procedures that look to avoid and reduce set up times will reduce job flow times and job lateness. They are particularly beneficial to "environments with:

- high utilizations (large queues),
- high family set up times relative to set up times,
- a low number of set up configurations (part families),
- and a high degree of instability with respect to job arrivals and run times (lot sizes)" (Wemmerlov 1992).

2.6 Standard Work

It is well documented that standard work is an important aspect of any process that is conducted in a manufacturing environment (Ohno 1988), (Liker 2004), (McIntosh, et al. 2001), (Monden 1998). Standard work is a process that standardizes a work sequence and displays the steps on a standard work sheet. A standard work sheets is used to train new operators or operators that are filling in for absent operators. According to Ohno (1988) there are three key elements of the standard work sheet (Ohno 1988):

- **Cycle Time;** The length of time (minutes and seconds) in which one unit is to be made,
- **Work Sequence;** the sequence of work,
- **Standard Inventory;** the minimum amount of goods to keep the process going.

It is understood that standard work sheets are the underlying support for Toyotas continuous improvement efforts because it is almost impossible to improve upon something unless a standard has been reached (Imai 1986). The standard work sheet provides a document which can still be improved upon and implemented almost immediately. This is best explained by Imai (1986): "There can be no improvement where there are no standards. The starting point in any improvement is to know exactly where one stands" (Imai 1986). This same logic can also be applied to set ups. By creating a standard work sheet it will become easier to see where set up improvements can be made.

Since standard work sheets are intended to continuously improve the processes within a company it can be understood that the documents need to allow flexibility for the operator to explore different, and better, ways of completing the task. The key to implementing standardization is to find the balance between having strict standards that will yield high quality products and be flexible enough to allow employees the freedom needed to innovate and create new methods (Liker 2004). Liker (2004) gives two important factors that are necessary to achieve this balance. First, the standards need to be structured and rigid enough to be useful guides. Second, the people doing the work need to improve the standards. Giving the employee an important role in designing the process will often give them the drive to create better standards.

There are three goals that are to be achieved by creating and revising standard work. The first goal is to achieve high productivity through the use of efficient and effective work of the workers. The second is to achieve line balancing among all processes in terms of production timing. The third is to minimize the WIP inventory by only producing the necessary number of units as set by the standard work sheet (Monden 1998).

Monden (1998) provides the necessary steps in creating an effective standard operations sheet for a process that involves multiple machines and multiple workers. First, it is necessary to find the required cycle time or takt time for the unit. It is best to think of the cycle time as the time between one unit coming off the line and the next. The cycle time is directly controlled by the demand.

$$\boldsymbol{cycle\ time} = \frac{\boldsymbol{Effective\ Daily\ Operating\ Time}}{\boldsymbol{Required\ Daily\ Quantity\ of\ Output}} \quad \textbf{(2.3)}$$

Second, is the completion time per unit which determines how long it takes to create one unit from start to beginning including the set up time. This time is found by timing the build time of the unit. Once completed the production capacity can be determined:

$$N = \frac{T}{C+m} \quad \textbf{(2.4)}$$

Where,

N = Production capacity in terms of units of output,

C = Completion time per unit,

m = set up time per unit,

T = Total operation time.

Figure 11 shows the part production capacity sheet which is a good way to organize and determine the above two calculations.

Part production capacity sheet	Item no.	Item name	Necessary quantity per day	Worker's name

Order of processes	Description of operations	Machine no.	Basic time: Manual operation time		Machine processing time		Completion time per unit		Tool's exchange: Exchange units	Exchange time	Production capacity (960 min)	References: manual operation ——— machine processing ········
			min.	sec.	min.	sec.	min.	sec.			units	
1	center drill	CD-300		07	1	20	1	27	80	1'00"	655	
2	chamfer	KA-350		09	1	35	1	44	20	30"	549	
									50	30"		
3	ream	KB-400		09	1	25	1	34	20	30"	606	
									40	30"		
4	ream	KC-450		10	1	18	1	28	20	30"	643	
2-1	mill	MS-100		(20)	(2	10)	(2	20)	1,000	7'00"	820	10" 10" 2'10"
2-2	mill	MS-101		(15)	(2	10)	(2	15)	1,000	7'00"		5" 10" 2'10"
	(two stands of machines)			18								[manual operation time per unit] = $\frac{20'' + 15''}{2}$ = 17.5" → 18"
3	bore	BA-235		(08)		(50)		(58)	500	5'00"	1,947	
	(two units processing at a time)			04				29				[manual operation time per unit] = $\frac{8''}{2}$ = 4"
4	gauge (1/5)			(18)								
	(one unit inspection in every five units)			09								[manual operation time per unit] = $\frac{18''}{2}$ = 9"
			total									

Figure 11: Part production capacity sheet (Monden 1998).

The third step is determining the standard operations routine sheet which is the routine that an operator will follow to complete the process. Figure 12 shows an example of a standard operations routine sheet.

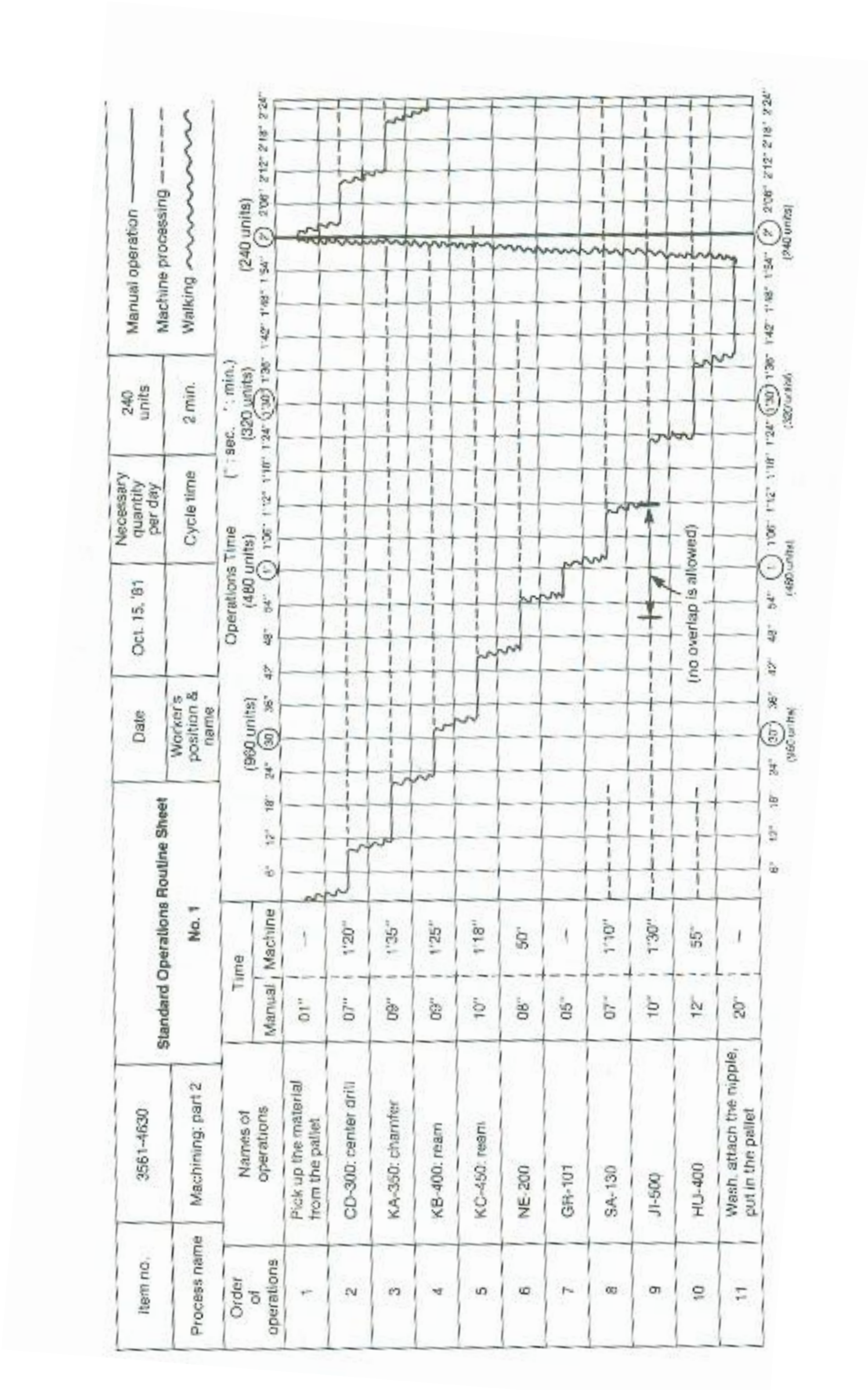

Figure 12: Standard operations routine sheet (Monden 1998)

Next, it is necessary to determine the standard quantity of WIP which is the minimum amount of WIP inventory that is held in the machines or is laid out between machines.

Finally, the standards operations sheet can be prepared. This document shows the required steps for the part to be finished. These steps may not be the same as the work operations routine sheet if there are multiple workers. This sheet is intended to be in a place that is visible or accessible to everyone. It is an overview of the process that ties together the four previous steps. An example of the standard operations routine sheet can be seen in Figure 13. It is important that the standard operations sheet includes the following items:

- Cycle time
- Operations Routine
- Standard quantity of work in process
- Net operating time
- Quality checks
- Safety Alerts.

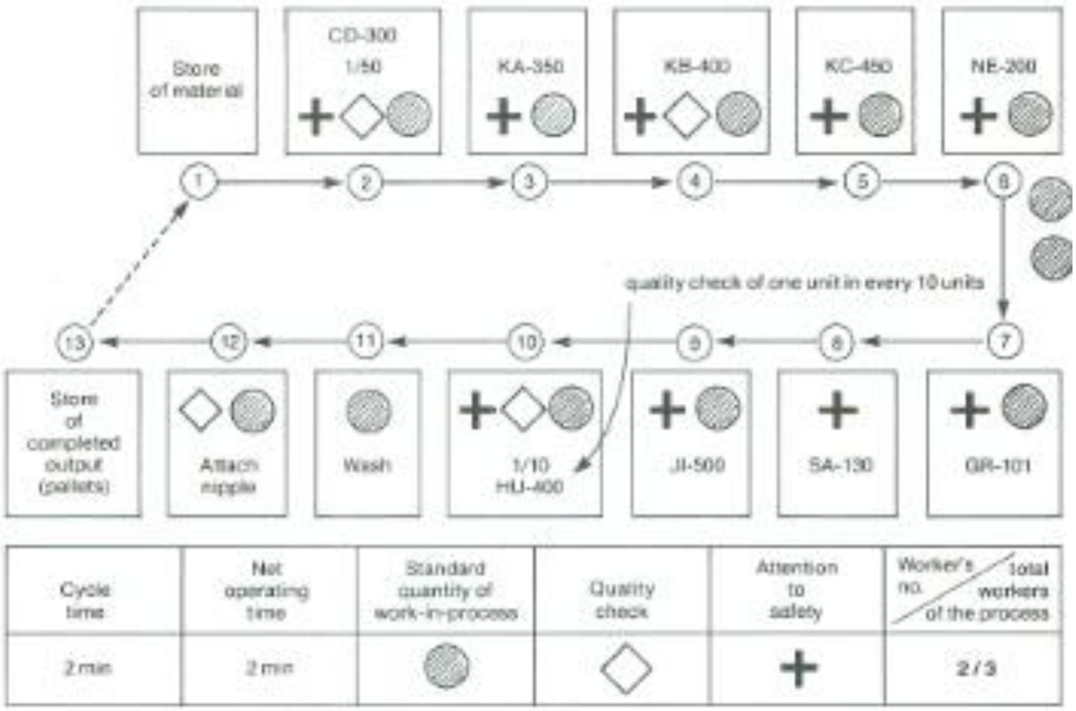

Figure 13: Standard operations sheet (Monden 1998)

Van Goubergen et al. (2002) has compiled a set of rules that can be applied to the set up process and can be used to determine work instruction sheets (Van Goubergen and Van Landeghem 2002). These rules are shown in Table 5.

9.	Method and organization
9.1	Separate on-line and off-line set-up activities, by asking the question 'Does the machine has to be stopped for this activity?'
9.2	Optimize the order in which the activities are performed to minimize movements and walking distance
9.3	In a line situation with more than one operator, divide the work on the different stations between the operators so that the machine on which the most activities need to be performed is not waiting
9.4	Balance the workload between the available operators and make separate instruction sheets per person
9.5	Use the Kipling questions on every activity of the set-up for critical review (What, where, when, who, how, why)
9.6	Provide set-up sets with all necessary tools and parts, determine the exact location where the tools and parts have to be placed before the actual set-up starts
9.7	Provide set-up instruction guides

Table 5: Design rules for efficient work methods (Van Goubergen and Van Landeghem 2002)

These rules provide a great structure as to how an engineer can go about creating a work instruction sheet for a set up. It starts with the basics of Shingo's SMED methodology. The next four steps are concerned with optimizing the routing and the scheduling of the operators. Steps 9.5 to 9.7 are concerned with creating the actual work instruction sheets themselves.

2.7 Chapter Summary

This chapter reviewed the literature that is concerned with changeover reduction, group technology, and standard work. It is evident that this area of research is a relevant problem in industry and has been studied at length.

Through the economic ordering quantity it is evident that changeover reduction will not only reduce inventory levels but it will also improve the OEE of the machines. In order to reduce changeover times, Shigeo Shingo developed the Single Minute Exchange of Die methodology that converts internal processes to external processes. His method has been proved to significantly reduce changeover times.

Many other approaches have been established that can be used to reduce changeover times, all of which can be categorized into either the ‘modification by design and methodology’ approach or the ‘design of a new system’ approach. Several other authors also developed step by step methods for implementing changeover reduction.

It has been found that group technology can be used to group parts with similar characteristics into families. The machines used to process these families can be placed next to each other on the plant floor; thus reducing the distance a job must travel. Group technology can also be used to schedule families with similar changeover characteristics next to each other on a schedule.

The literature concerned with standard work was also reviewed. Standard work is a process that standardizes a work sequence so that it can be improved upon in the future. Many methods and worksheets, such as the standard operations sheet, have been developed as a means for implementing standard work.

CHAPTER 3 – INITIAL OBSERVATIONS

In order to understand the problems that are presented by long changeover times it will be necessary to analyze current changeover processes. This provides insight to the specific steps that need to be performed in order to complete a successful changeover. Six changeovers were filmed and analyzed. The filming process involved mounting a camera on a tripod to film the duration of the changeover. It was desired to capture the entire changeover, that is, the time between the last good part "A" and the first good part "B". The person filming the changeovers did not interfere with or help the operators in any way throughout the process. Once the film was gathered it was analyzed and critiqued. According to Van Goubergen, et al. (2001) "The benefits of making these videos are:

- A detailed overview of all the activities
- The immediate availability of time data of all activities
- The possibility to review activities; if necessary in slow motion
- The fact the people performing the set up can look at themselves 'from a distance' and realize that things can be improved
- The understanding of the duration of time: 'how long takes a minute'" (Van Goubergen and Van Landeeghem 2001).

3.1 Analysis Methods

The changeovers will be analyzed using a Changeover Analysis Sheet which records the work elements, finish times, net times, internal activities, external activities, and the main function of the activity. An example of a blank Changeover Analysis Sheet can be found in Figure 14.

Changeover Analysis Sheet (XX_XX)						Unique Properties:
Machine: Chiron 4	Changeover Personnel:			Date :		
Changed From:X and X	Changed To: X and X			Total Time:		
No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D	Notes:
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
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34						
35						
36						
37						

Figure 14: Proposed changeover analysis sheet

The work element column of Figure 14 is a description of the work that is being done. The finish time is the time when the work element is finished. The net time is the amount of time that the work element took to accomplish. The internal/external column denotes if the work element is internal or external and the last column denotes the main function of the work element. There are four main functions, or steps, that were described through Shingo's SMED methodology (Shingo 1985). A fifth main function, distractions, was added as an additional main function. The definitions of the main functions have been altered so that they are more specific to this work and are defined as follows:

- Preparation and Aftercare (P) – Any activity that is done in order to prepare the machine and the jobs that are coming off of or going onto the machine. Typically these tasks can be done externally but it is often found that they are done internally.
- Mounting Tools and Fixtures (M) – These are the activities that involve removing old fixtures and tools and mounting the new ones.
- Measurements, Settings, and Calibrations (S) – In order to prepare the machine for the new jobs it is often required to make adjustments to the machine. In this case setting tool heights and preparing CNC programs falls into this category.
- Trial Run (T) – When using CNC machines it is necessary to "prove" the tool paths in order to verify that the tools are in the correct location on the tool magazine and that they are cutting properly. This involves watching the machine when each tool makes its first cut. In most cases the operator will slow the feed rate to make sure that the tool is cutting correctly. This process is time consuming but it must be done in order to increase quality

and reduce scrap rates. If the trial run is successful then it will yield a batch of good parts; however, this time is still considered to be part of the changeover.

- Distractions (D) – Anything that takes the operator away from completing the task at hand.

The first three main functions were further divided into smaller groups:

- Preparation and Aftercare
    - Preparing to set tool heights
    - Paper work
    - Cleaning/Organizing
    - Removing finished goods and retrieving raw materials
    - Finishing operations from the previous job
- Mounting Tools and Fixtures
    - Removing and attaching fixtures
    - Cleaning the machine or fixtures
    - Removing and attaching tools
- Measurements, Settings, and Calibrations
    - Setting tool heights
    - Inspecting and calibrating
    - Loading CNC programs

After analyzing the videos and categorizing the elements of the changeover into the steps described in this section, it will be possible to determine which elements are taking too much time. It will also allow an opportunity to analyze which elements are being done internally when they could be done externally. As mentioned in the literature review, it is critical to maximize the work elements that are done externally, thus yielding more time for the machine to process parts.

The company being studied has done a good job of converting some of the work elements to external ones; however, there are still many improvements that can be made. It is understood that all preparation and aftercare activities should be done externally and that some of the measurements, settings, and calibrations activities can also be done externally. The trial runs are expected to be done internally since it is part of the run up phase of the changeover. The mounting of tools and fixtures are also expected to be done internally. After viewing the videos it became clear that too much of the changeover is being done internally and that new methods can be developed to significantly reduce the internal time. The observations and analysis of these videos will be discussed in sections 3.2 and 3.3.

3.2 Observations

The vertical CNC machining area consists of four primary machines that are used for production. There is a supervisor that is responsible for creating the schedule that is given to the head operator. The head operator is in charge of preparing the tools (tool setting) for the upcoming jobs. The head operator will also run one of the machines and perform changeovers for operators that are not qualified to conduct the changeovers themselves. It has been found that there are many types of changeover that are done on a regular basis; however, they all have several steps that are necessary for a successful changeover. A brief description of the steps required to conduct the changeovers is as follows:

1. Tool Setting – When a new job requires new tools, the offsets for the tool heights must be measured and then entered into the machine. In order to do so, the tools are all placed into tool holders; the heights are measured digitally, and this data is then transferred to the computer. Once each tool height has been entered into the CNC programs the tools are put on a holding rack on the side of the machine. The set up sheet, with the offset values, is also posted on the machine. This process is all done externally before the changeover begins.
2. Removing and Installing Fixtures – The fixtures from the old jobs are removed from the pallets and the new ones are attached. Most of the time this is done internally however sometimes the fixtures are removed and installed when the operator has idle time after the last cycle changeover. The fixtures are then returned to storage.

3. Finished Goods and Raw Materials Bins – Next, the old finished goods bins are removed and replaced with the new ones. The raw material bins are also removed and replaced with new ones. This step can be completed at different stages of the changeover; however it has been observed that this process is often done internally.
4. Attaching Raw Materials – The raw materials for each job need to be attached so that the trial runs can be conducted (considered as part of the trial run).
5. Programming and Loading Tools – Next the new CNC programs are loaded onto the machine. Then the old tools are removed from the tool magazine and the new tools are installed.
6. Proving – This is often the last step in the changeover process and involves proving the tool path during the trial run. When this step is complete the finished goods are removed and inspected.

In order to clearly refer to each changeover, a naming convention was developed that shows which jobs were taken off the machine and which were put on the machine. The convention is as follows:

OldJobTable1 OldJobTable2_NewJobTable1 NewJobTable2

For example, a changeover that went from job A and job B to job C and job D would be displayed as AB_CD. Each letter corresponds to the part numbers that are used by the company. The six changeovers that were analyzed were:

1. AB_AC
2. C_DE
3. FG_HI
4. JK_LM
5. N1N2_O
6. PQ_RL

The changeovers that were selected are meant to encompass the wide range of different types of changeovers that are done on a regular basis. Each changeover has several unique properties that are helpful to understand in order to find methods that can reduce changeover times.

The first changeover, AB_AC is unique in that the job on table 1 was not changed over. This idea of only changing over one of the tables will prove to be a valuable strategy and will be discussed in length in chapter 5. This changeover is also unique in that it has a complex proving process since there are three orientations for job C. To prove the first orientation the first set of raw materials is loaded on the fixture and then proved. To prove the second orientation, the first set of RMs is moved to the second orientation and a new set of RMs is loaded. This process continues for the third orientation as well. The result is a trial run that takes 11 minutes longer than the average time.

Changeover C_DE is unique in that there is only one old job that is being changed over. There is only one old job since the run times of the old jobs did not match, which means that the fixture for the job that finished first was removed during a cycle changeover. Since the fixture was removed prior to the changeover, this is a good example of converting internal activities to external ones. This changeover also has a long trial run because part D has two orientations and part E has 3 orientations.

The next changeover, FG_HI, has two unique properties that will prove to be major time savers and will be discussed in length in chapter 5. The first is the fact that all four jobs share the same tools, which means that setting the tool heights and exchanging tools will not be necessary. The operator will still have to copy the offset values to the new programs but this takes 4 minutes and 30 seconds less than the traditional method. The second unique property of this changeover is that jobs F and H share a fixture and therefore only one fixture will have to be changed over. This saves 3.26 minutes of internal time.

Changeover JK_LM is the best representation of a full changeover. It is also a good example of converting an internal task to an external task. This was done by removing fixture J during a cycle changeover previous to the changeover.

Changeover, N1N2_O is an example of the difficulties that arise in scheduling jobs to machines with pallet changers. Since job O requires 10 tools, there were only 2 tool locations left on the magazine. Because of this, there were no other jobs on the schedule that could be paired with job O. This meant there was that there is only one job that needs to be set up during the changeover. The other unique property was that the previous job used two fixtures meaning the job needed two pallets

The last changeover, PQ_RL, is another example of a full changeover where one of the fixtures was removed during a cycle changeover prior to the changeover.

These six changeovers were chosen because they cover the wide range of scenarios that are seen when jobs are changed over. The average changeover has been found to take 57.78 minutes with a standard deviation of 8.6 minutes. The longest changeover took 69.45 minutes while the shortest took only 32.43 minutes.

It is important to note that due the large quantity of part numbers that are processed by the machine shop there is a very low chance that the same changeover will happen again in the near future. For this reason each changeover could only be filmed once. It is also understood that if the process of the changeovers can be improved upon then a reduction in the average changeover time will be seen; and therefore, analyzing the exact same changeover is not necessary.

3.3 Analysis

After the changeovers were filmed they were analyzed through the changeover analysis sheet and Pareto charts that show the breakdown for each changeover. The changeover analysis sheet for JK_LM is shown as an example in Figure 15. For this changeover the head operator performed the first eleven tasks (tool setting) and the operator performed the remaining tasks. The remaining five changeover analysis sheets and the corresponding data can be found in Appendix I.

Changeover Analysis Sheet (JK_LM)						Unique Properties: *Fixture K removed previous to changeover
Machine: Chiron 4		Changeover Personnel: Operator and Head Operator		Date: 12/21/2010		
Changed From:J and K		Changed To: L and M		Total Time: 1:09:27		
No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D	Notes:
1	Start	0:00:00				
2	Pull Cart Over	0:00:15	0:00:15	E	P	
3	Open Programs and Delete Old Offsets	0:02:00	0:01:45	E	S	
4	Prep Programs	0:04:03	0:02:03	E	P	
5	Set Tool Heights	0:08:36	0:04:33	E	S	
6	Close Programs	0:08:50	0:00:14	E	S	
7	Print and Retrieve Set up Sheets	0:09:26	0:00:36	E	P	
8	Place old Tools in Cart	0:09:57	0:00:31	E	P	
9	Double Check Offset Values	0:10:50	0:00:53	E	S	
10	Place Sheets on Set up Cart	0:11:05	0:00:15	E	S	
11	Paperwork, Disconnect Cart	0:12:20	0:01:15	E	P	
12	Start	0:14:08				
13	Remove Fixture (J)	0:15:50	0:01:42	I	M	
14	Distraction	0:16:28	0:00:38	I	D	
15	Clean Fixture	0:17:15	0:00:47	I	M	
16	Clean Table	0:17:55	0:00:40	I	M	
17	Organize Carts	0:18:25	0:00:30	I	P	
18	Paperwork	0:18:44	0:00:19	I	P	
19	Bring FGs to Pickup Area	0:19:24	0:00:40	I	P	
20	Sweep	0:21:58	0:02:34	I	P	
21	Return Old Fixture and Get New Fixture (L)	0:23:59	0:02:01	I	M	
22	Attach Fixture (L)	0:25:21	0:01:22	I	M	
23	Get RMs (L)	0:26:30	0:01:09	I	P	
24	Get FGs Boxes	0:27:12	0:00:42	I	P	
25	Attach RMs (L)	0:28:35	0:01:23	I	T	
26	Flip Table	0:29:00	0:00:25	I	M	
27	Attach Fixture (M)	0:30:48	0:01:48	I	M	
28	Get RM (M)	0:34:55	0:04:07	I	P	*Also returns RM crate to pick up area
29	Attach RM (M)	0:36:34	0:01:39	I	T	
30	Place Set up Sheet on Machine	0:37:06	0:00:32	I	P	
31	Remove Old Tools and Attach New Ones	0:38:50	0:01:44	I	M	*5 Tools
32	Prepare Programs	0:42:44	0:03:54	I	S	
33	Prove Tool Path (L)	0:53:24	0:10:40	I	T	* Get FG bin while proving
34	Flip Table, Prove (M 1st Orientation)	0:55:45	0:02:21	I	T	
35	Attach RMs to fixture (M)	0:58:50	0:03:05	I	T	
36	Flip Table, Prove (M 2nd Orientation)	1:03:02	0:04:12	I	T	
37	Inspect (L)	1:08:04	0:05:02	I	S	
38	Attach RM (L)	1:09:49	0:01:45	E	T	
39	Remove FGs (M) Changeover complete	1:11:15	0:01:26	E	T	
40	Flip Table, Cylce Changeover (M) (Changeover complete)	1:14:45	0:03:30			
41	Clean L from previous cycle (Changeover complete)	1:15:39	0:00:54			
41	Wait for M to finish (Changeover complete)	1:19:32	0:03:53			

Figure 15: Example of a changeover analysis sheet

Once each changeover has been analyzed, the percent of time that each main function consumes can be shown graphically though a Pareto chart. This will also show the proportion of each main function that is devoted towards internal and external operations. The Pareto chart for changeover JK_LM is shown in Figure 16. The Pareto Charts for the remaining changeover can be found in a Appendix II.

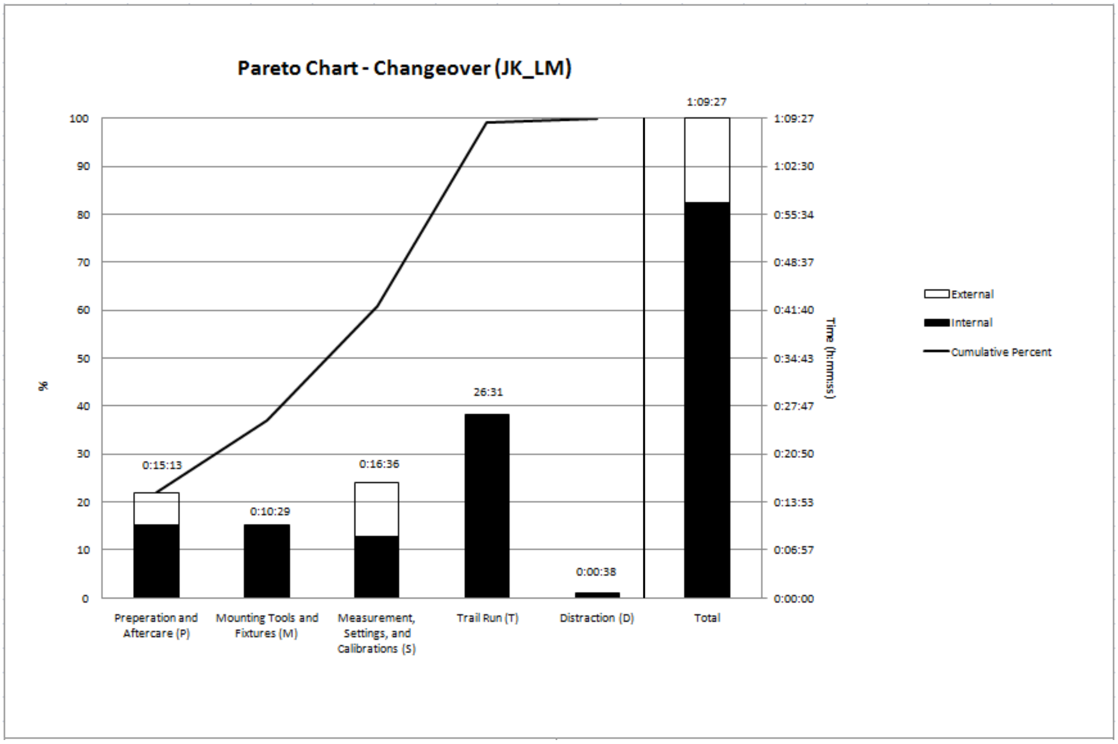


Figure 16: Pareto Chart – Changeover times for JK_LM

The left vertical axis of the graph in figure 16 shows the percent of the total time that each main function represents. The right vertical axis of the graph shows the time that each main function represents. The right most column on the graph shows the total time that was required to complete the changeover, which in this case is just over one hour. By looking at the graph it can be seen that only 18% of the changeover was done externally and the remaining 82% of the changeover was done internally.

Understanding how much of each main function is being done internally and externally shows which main functions are more important to convert to external ones, or to attempt to reduce. For instance, the preparation and aftercare category is mainly made up of internal activities. Given the tasks in this category, it should be possible to convert all of the actives to external ones. For instance, cleaning, getting raw materials, organizing crates and bins, and getting finished goods bins can all be done while the machine is running.

It is seen that mounting tools and fixtures is all done internally, and due to the nature of mounting tools and fixtures it is not possible for the entire process to be done externally. However, some of the tasks can be done externally in order to reduce the internal time required to mount the tools and fixtures. For instance, the fixtures should be retrieved and organized onto carts when the machine is running.

It is also important to note that during this changeover, one of the fixtures was removed prior to the changeover, meaning it was removed during a cycle changeover. This strategy of completing tasks during cycle changeovers is a very important concept and is an effective way to convert internal activities to external ones, thus reducing the changeover times dramatically. While this effort in reducing internal time is not reflected in this time study it is noted as an effective way to convert an internal activity to an external one.

Figure 17 displays the average changeover times and the average time of each main function, for the six changeovers that were analyzed in this research. By looking at this graph it is again clear that too much of the changeover is being done internally (72.3%) and not enough is being done externally (27.7%). It is also seen that the trial run consists of 41% of the changeover and this is all done internally. The trial run consists of monitoring each step of the machining process as it starts, but the operator often has idle time in between steps that can be used to complete other tasks. In Figure 17, the right most column represents the total average time and the remaining columns represent the averages for each main function. Each column is also broken down into internal and external operations.

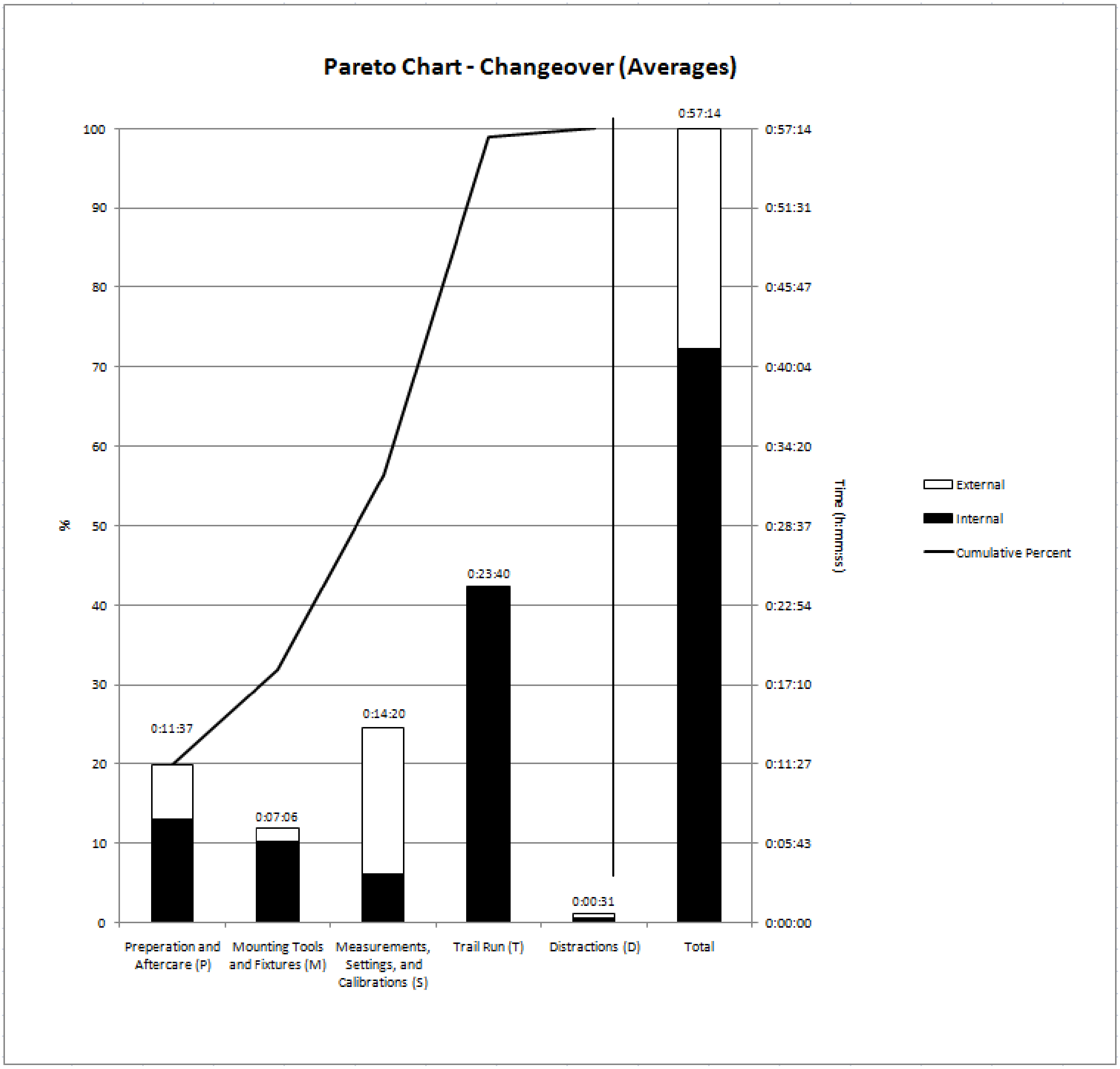


Figure 17: Pareto Chart – Average changeover times

To further clarify the changeover process, the first three main functions, namely, preparation and aftercare, mounting tools and fixtures, and measurements, setting, and calibrations were divided into the activities that make up each category.

The average times for these functions can be seen in Figure 18, Figure 19, and Figure 20. The last two main functions, trial run and distractions, were not further divided because each of these functions only has one activity.

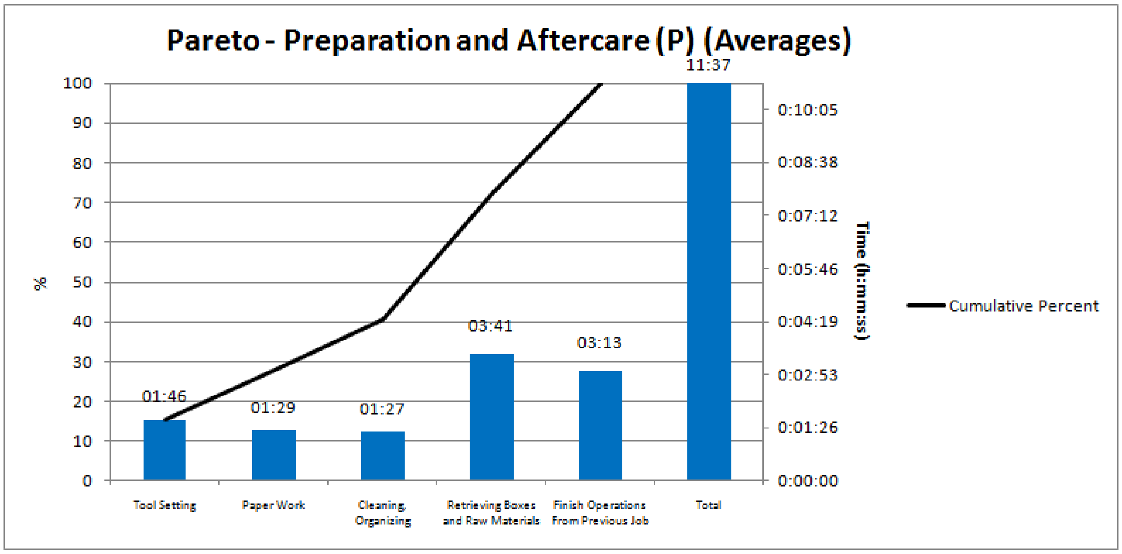


Figure 18: Pareto Chart – Average times for preparation and aftercare

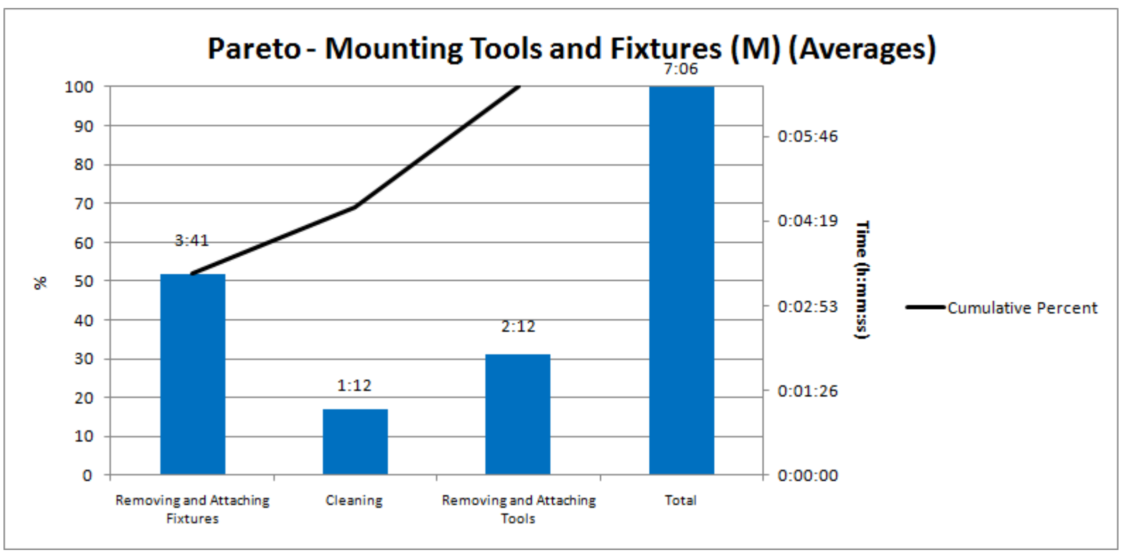


Figure 19: Pareto Chart – Average times for mounting tools and fixtures

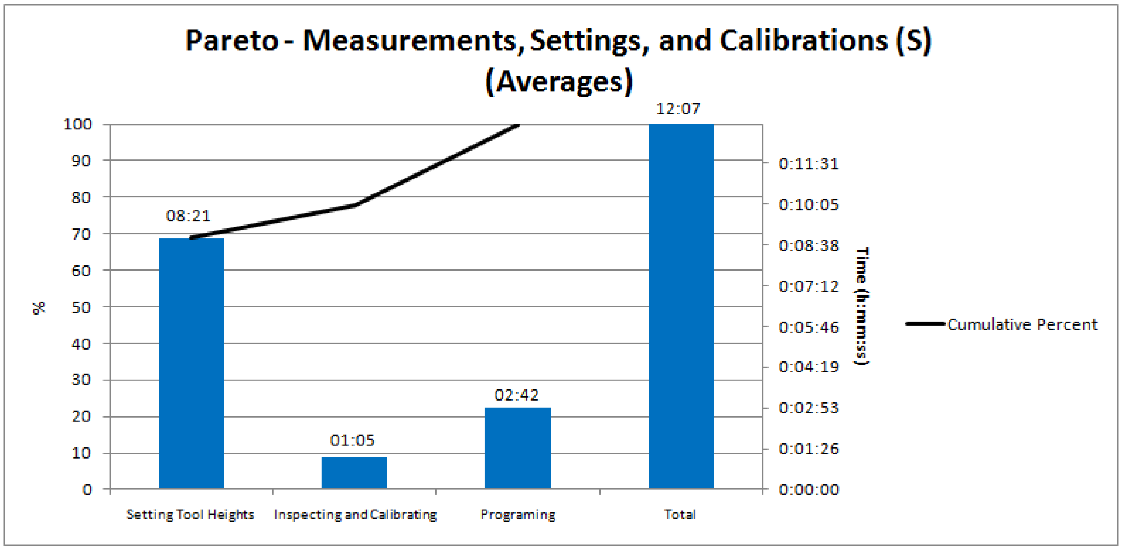


Figure 20: Pareto Chart – Average times for measurements, settings, and calibrations

Figures 18, 19, and 20 show how long each activity takes and which ones are the most time consuming. Clearly, the activities that take up the most amount of time should be targeted first and reduced as much as possible. Figure 18 shows that retrieving boxes and raw materials takes the longest and should therefore be reduced. Also, this activity is considered a non-value adding activity. A value adding activity is one that adds value to the product as seen by the end user. Since retrieving bins for the machined parts does not add value to the product, this is regarded as a non-value adding activity. Such a task is necessary, but is non-value adding to the parts being manufactured, and should be done at a later time, i.e. when the machine is running.

In Figure 19, it is seen that removing and attaching fixtures takes the longest and therefore efforts such as using quick fastening devices should be made to reduce this time. Figure 20 shows that setting the tool heights takes the most time, however it is noted that this is all done externally which is an excellent example of converting an internal operation to an external one.

There are several important elements that must be completed during each changeover. These elements are displayed in Figure 21. The important elements consist of setting tool heights, removing and cleaning fixtures, attaching fixtures, removing and attaching tools, programming and proving. It will be seen through chapter 5 that some of these tasks can be eliminated if the jobs are scheduled differently.

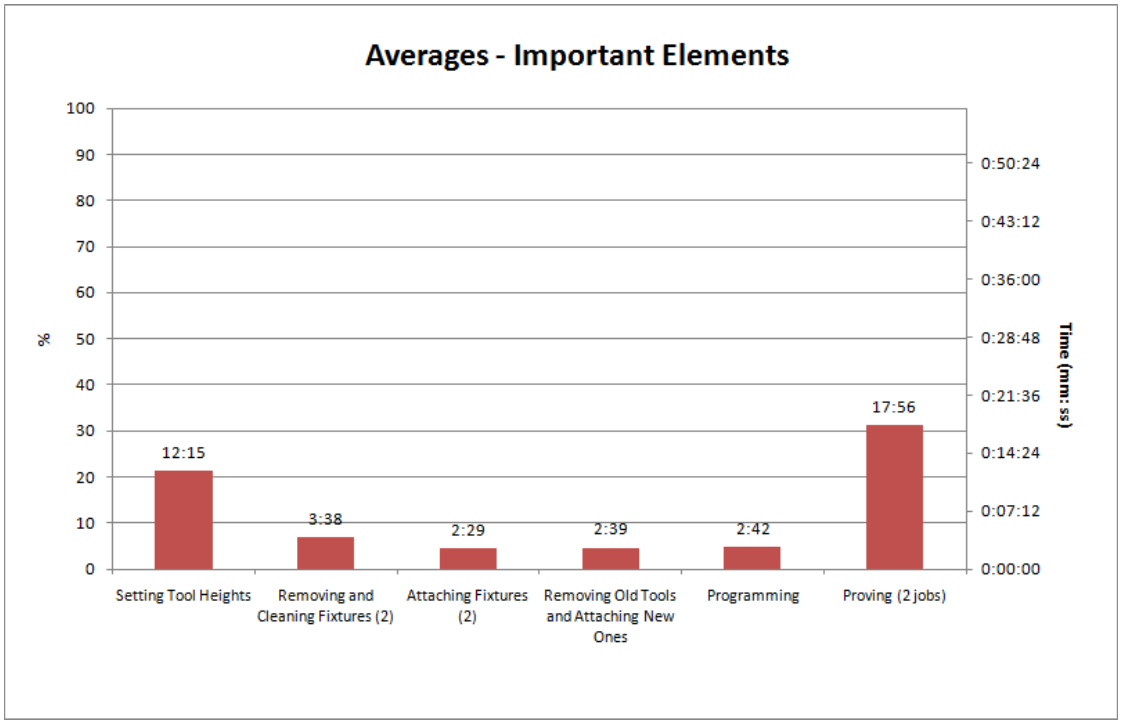


Figure 21: Average times of the necessary elements for each changeover

After filming and establishing the basic steps required for these changeovers it was possible to break down the changeovers into specific work elements. Then it was possible to denote each element as internal or external which is the goal for Stage 1 of Shingo's SMED methodology. Further breaking down the changeovers into smaller categories will provide insight into how to accomplish Stage 2 of Shingo's SMED methodology; converting internal to external set up. This will be the main focus of section 3.4.

3.4 Proposed Changeover Methodology

A methodology has been developed that includes the steps necessary for all changeovers. The main goal of this method is to convert internal steps to external steps. As mentioned, there are many different changeover scenarios that have been analyzed in this research; however, the method discussed here will be for a full changeover that requires all jobs, fixtures, and tools to be changed over.

When observing and analyzing the film, two important observations were made that could reduce internal times substantially. The first is that while proving the tool path, the operator has a significant amount of idle time. The second is that during cycle changeovers there is also some idle time where the operator could be performing other tasks.

Proving the tool path consists of watching each tool as it makes its first cut. This ensures that the correct tools are in the correct locations of the tool magazine and that the correct program has been loaded onto the machine. In order to prove the tool path the operator will step through the CNC program. This will allow the operator to watch each tool make its first cut. Once it has been verified that the tool is cutting properly the operator has idle time while the machine runs through the remaining operations for that tool. Since the machine is stepping through the program the machine will stop and wait for the operator once it is finished with each tool. This way the operator will not risk the chance of being absent to prove the next tool. This idle time can be used to complete other tasks for the changeover.

The cycle changeover is another place to find idle time for the operators. This method takes advantage of the fact that the machines in this study utilize pallet swappers (or table changers). These machines have two tables, one in the machining area (under the cutter head) and one in the access area (located on the side of the machine). While table 1 is in the machining area the pieces are being cut according to the CNC program. At this time, table 2 is accessible to the operator and it is at this time when the operator will perform the cycle changeover. This cycle changeover is where the finished goods are removed from the fixture and the new raw materials are attached to the fixture. If the cycle changeover is less than the cycle time of the CNC program, then the operator will have idle time to perform activities for an upcoming or recently finished changeover. On average, the cycle time is 8.50 minutes and the cycle changeover time is 5.9 minutes which leaves 2.6 minutes to perform other tasks.

The method presented here will attempt to utilize the idle time found during cycle changeovers and the tool proving process. Figure 22 shows an ideal changeover that will substantially reduce the cycle changeover time.

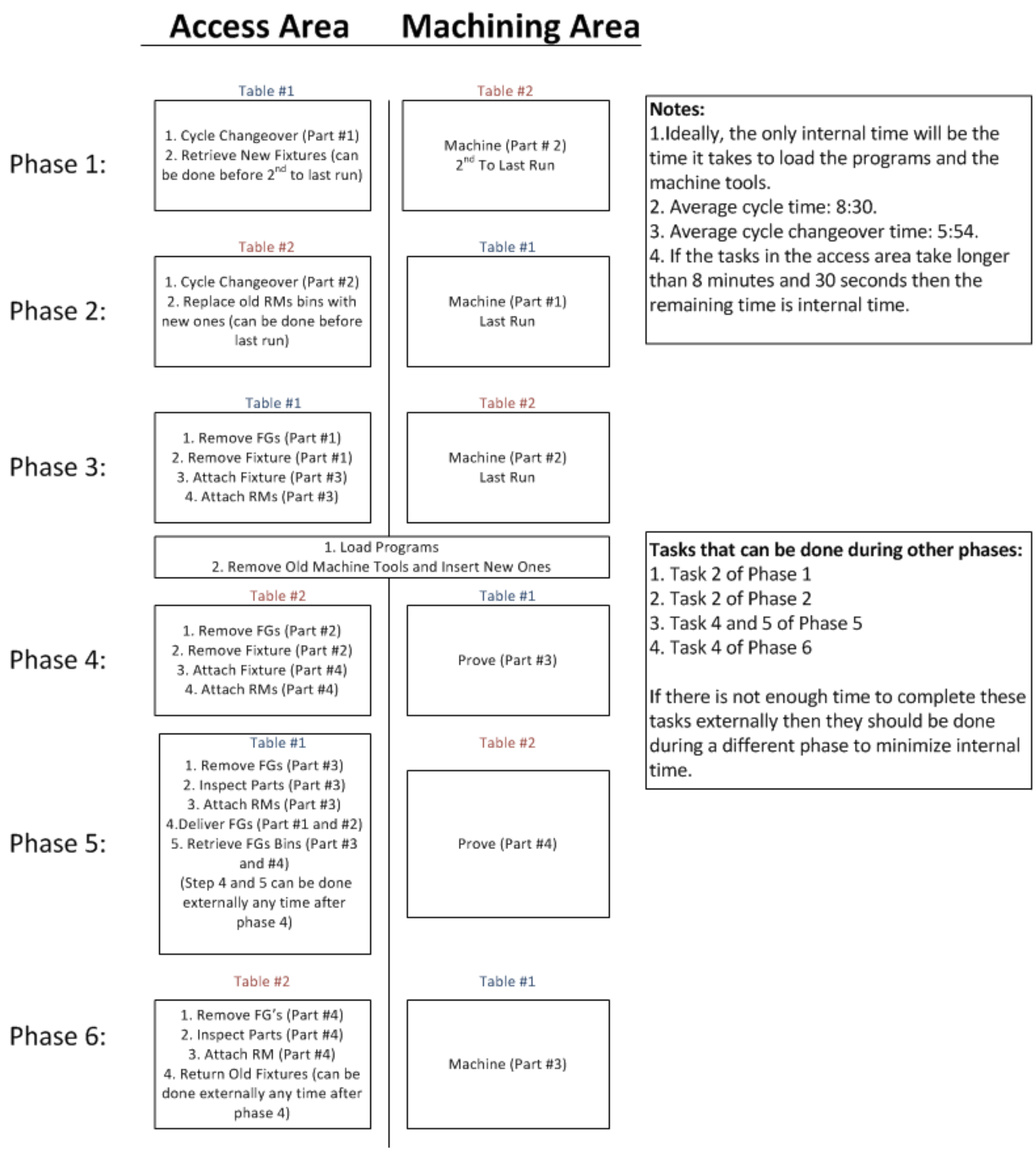


Figure 22: Ideal changeover

In the first phase of the changeover, the operator will perform a cycle changeover on table 1 and with the remaining time the operator will retrieve the new fixtures. During this phase, the job on table 2 will be on its next-to-last cycle. During phase two, the operator will perform a cycle changeover to part #2. He will also remove the old raw material bins and replace them with the new ones. During phase three, the operator will remove the finished goods and the fixture for part #1. He will also attach the fixture and the raw materials for part #3. Once this has been finished the CNC programs and the tools can be loaded onto the machine. This time will be exclusively internal so performing these tasks should be done in the most efficient manner possible. During phase four, the operator will begin proving part #3 and during the idle time the operator can remove fixture #2 and attach the fixture and raw materials for fixture #4. Once proving is finished on part #3, then part #4 can be proved out and a standard cycle changeover can be completed for part #3. During this time it will be necessary to inspect the newly machined parts and replace the old FG bins with the new ones. In phase six, a standard cycle changeover can be performed for part #4. The parts can be inspected and the old fixtures can be returned to the fixture rack. At this point, the changeover should be complete. If there are any other tasks that need to be completed then they should be done during the next cycle changeover.

It is noted that if the tasks in the access area take longer than the cycle time then the remaining time will be internal time. It is also noted that if all of the tasks in the access area are able to be completed externally then the only internal time will be the time it takes to load the CNC programs and the new tools. This should be the ultimate goal for each changeover as it will result in a changeover that only requires 5.35 minutes.

In order to maximize how many tasks are done externally, some of the tasks for the access area can be moved to a different phase of the changeover. The tasks that can be moved to other phases of the changeover are listed in Figure 22. The idea of completing tasks externally is very important and the operator should always be thinking of ways to maximize the number of tasks that are done externally.

One drawback of this methodology is the possible negative psychological effects that it may have on the operators. As mentioned, the goal of the methodology is to have the operators perform as many activities as possible during the operator's idle time, thus possibly leading to overexertion of the operators. Also, the operators may reject the methodology since they may feel as though it results in more work for them. These psychological effects should be considered when implementing this methodology; however, such effects are beyond the scope of this research. Perhaps one way of encouraging quick changeovers is to create an incentive for operators to strive for reduced changeover times.

3.4.1 Example

This method can be applied to the changeovers that have been analyzed in this research. Figure 23 shows how much time could be saved when this method was applied to changeover JK_LM. If the tasks were arranged as they are shown in Figure 23 then a 39% reduction in internal changeover time should be seen.

				Changeover JK_LM	
	Access Area (operator)			Machining Area (Machine)	
	Tasks	Time		Time	Tasks
Phase 1	Cycle Changeover (J) Average	0:05:54		0:11:30	Machine (K)
	Retrieve Fixtures (L and M)	0:02:01			
	Total	0:07:55		0:11:30	Total
				0:00:00	Internal Time
Phase 2	Cycle Changeover (K) Average	0:05:54		0:09:00	Machine (J)
	Replace Old RMs bins with new ones	0:05:16			
	Total	0:11:10		0:09:00	
				0:02:10	Internal Time
Phase 3	Remove FGs (1/2 cycle changeover time) Ave.	0:02:57		0:11:30	Machine (K)
	Remove Fixture (J)	0:01:42			
	Attach Fixture (L)	0:01:22			
	Attach RM (1/2 cycle changeover time) Ave.	0:01:23			
	Total	0:07:24		0:11:30	Total
				0:00:00	Internal Time
Loading Tools and Programs	Load Tools	0:01:44			
	Programming	0:03:54			
		0:05:38			
				0:05:38	Internal Time
Phase 4	Remove FGs (K) (1/2 cycle changeover time)	0:02:57		0:03:42	Idle Proving Time
	Remove Fixture (K)	0:02:02			(Proving L)
	Attach Fixture (M)	0:01:48			
	Attach RMs (M)	0:01:39			
	Total	0:07:24		0:03:42	Total
				0:03:42	Internal Time
Phase 5	Remove FGs and Inspect (L)	0:05:02		0:00:32	Idle Proving Time
	Attach RMs to Fixture (L)	0:01:45			(Proving 1st Orientation M)
	Total	0:06:47		0:00:32	Total
				0:06:15	Internal Time
Phase 6	Attach RMs to Fixture (M)	0:03:05		0	No machining can take place
	Total	0:03:05		0	(L only has one orientation)
				0:03:05	internal Time
Phase 7	Deliver FGs (J and K)	0:00:40		0:02:13	Idle Proving Time
	Retrieve FGs bins (L and M)	0:00:42			(Proving 2nd Orientation M)
	Total	0:01:22			
				0:00:00	Internal Time
Phase 8	Cycle Changeover (M)	0:07:30		0:08:30	Machine (L)
	Inspect	0:00:00			
	Return Old Fixtures (J and K)	0:02:01		0:08:30	Total
	Total		0:09:31	0:01:01	Internal Time
				0:10:46	Remaining Proving Time
				0:32:37	Total Internal Time
				0:53:18	Original Internal Time
				0:20:41	Time Savings
				38.80550344	Percent Reduction

Figure 23: Ideal changeover for JK_LM

As mentioned, this method takes advantage of idle time during cycle changeovers. During phase 1, the cycle time is 11.50 minutes which gives the operator enough time to complete all of the necessary tasks for that phase externally. This means there will be no internal time during phase one. Phase two requires 11.16 minutes for the operator to complete the necessary tasks and the machine requires only 9 minutes to run the cycle. This means there will be 2.66 minutes of internal time. The same method was applied to the remaining phases of the operations to determine the total internal time.

Since part M has two orientations, it is necessary to have eight phases in order to complete this changeover. As mentioned, it is acceptable to add more phases to the changeover if this will allow more tasks to be done during idle time. In this example, the tasks of delivering FGs, retrieving FGs bins, and returning old fixtures were all done during different phases than as specified in Figure 22.

Given that this is just one example, it is understood that times for other changeovers will vary dramatically; however, if this method is used then a reduction in changeover time should be seen.

3.4.2 Use as a Standard Work Sheet

The proposed changeover methodology can also be used as a standard work sheet that is to be followed and modified by the operators. The methodology proposed in this thesis standardizes the changeover process for the CNC milling machines at the company being studied and should be used as a standard work sheet.

The proposed changeover methodology is different than most standard work sheets because it describes the process of a changeover and not the process to produce a good. However, the proposed changeover methodology is still a process that should be standardized.

As mentioned in the literature review, there are three key elements to a standard work sheet, namely the cycle time, the work sequence, and the standard inventory. The cycle time for the first three phases is to be less than the cycle time for the machining process during that phase. And the cycle time for the other phases is to be less than the idle proving time. Perhaps the most important part of the standard work sheet, the work sequence, is well established in the proposed changeover methodology. Lastly, is the standard inventory, which is different for the changeover process. The standard inventory normally consists of the minimum amount of goods to keep the process going, which is not directly applicable to the changeover process. However, the standard inventory can consist of a general list of tools and supplies needed for the changeover, i.e. "new fixtures, new raw materials bins, and new finished goods bins".

The main purpose of a standard work sheet is to establish a standard that can be followed by the workers, and one that can be modified and improved upon. This philosophy directly supports the idea of continuous improvement and should be applied to the proposed changeover methodology.

3.5 Suggestions

In order to increase the idle time that is seen during cycle changeovers the cycle changeover times need to be minimized. Because a cycle changeover is mainly comprised of attaching and detaching work pieces it is necessary to look at quick fastening devices that can speed up cycle changeovers.

Figure 24 displays several methods that can reduce fastening times (Winco 2010), (McMaster-Carr 2010), (LeanSupermarket 2010), (Shingo 1985). One way to reduce fastening times is to eliminate the need to remove the nuts from the studs on the fixture. This is possible through the pear shaped hole method and the swing C-washer method. With these methods, the nut does not have to be removed from the stud. To improve upon this method, a stop can be welded to the top of the stud so that the nut will not unthread off of the stud while using the pneumatic drill. Quick nuts can be used so that the operator can slip the nuts down the stud and snug it up to the fixture with the pneumatic drill. Another easy way to eliminate excess turning of nuts is to simply shorten the length of the studs. Perhaps the best way to reduce fastening times is to eliminate the need to tighten screws at all. This can be possible with the use of a toggle clamp.

Figure 24: Quick fastening devices (Winco 2010), (McMaster-Carr 2010), (LeanSupermarket 2010), (Shingo 1985)

If time allows, another suggestion is to complete some of the tasks during different phases of the changeover. For example, if the operator realizes that there is more idle time during phase four, then it may be possible to return the old fixtures to the rack during this idle time. Also, if there is not enough time to retrieve the new FGs bins during phase five then the operator can wait until phase six to retrieve the empty FGs bins. The list of tasks that can be done during different phases of the changeover is listed in Figure 22.

Most of the time, there are multiple orientations for one job which will require the operator to prove the jobs in steps. This means that there will be less idle time during each step. Therefore, the operator will have to wait to perform other tasks until the second orientation is being proved. This issue will vary from job to job but if the operator has a firm understanding of the method and can keep track of which tasks still need to be finished, then he can alter when the tasks are completed.

Another way to help improve changeover times is to take the burden off of the operator. For instance, the material handler can place the raw materials directly at the machines instead of placing them in the staging area. The same can be done with finished goods too. In order to communicate to the material handler a red piece of paper can be placed on the raw materials to signal the material handler to come get the raw materials that are no longer needed and then retrieve the raw materials that will be needed for the next job. Again, this same idea can be used for the finished goods as well.

A different way to take the burden off of the operator is to give the responsibility of preparing changeovers to another worker. This worker can organize the finished goods bins, the raw materials, and the fixtures that will be needed for the new jobs. Also, once one job is complete, the worker can remove the old raw materials and the finished goods. The main goal for this worker is to take care of all of the preparation and aftercare so that the operator will not be held back by these tasks during the changeover. It is noted that assigning additional resources means that the company will have to reallocate or hire another worker which could be costly; however, assigning more resources to the changeover process will always reduce internal time.

The suggestions discussed here are all examples of ways to streamline many aspects of the changeover. This method of streamlining the changeover is Shingo's stage 3 of his SMED methodology. Other methods of streamlining the changeovers such as time and motion studies, spaghetti diagrams, and rearranging work stations is an excellent area of future work. However such studies are beyond the scope of this work. This chapter has outlined how to utilize Shingo's SMED methodology in order to significantly reduce changeover times and it has been found that many conclusions can be drawn from this chapter.

3.6 Chapter Summary

Several changeovers have been observed and analyzed and it has been found that there are multiple areas of the changeover that can be improved upon to decrease changeover times. More specifically it has been observed that 72.3% of the changeover is done internally and that only 27.7% of the changeover is done externally. It was also observed that the operator will have idle time during cycle changeovers and while the operator is proving the tool path. The method outlined in Figure 22 shows an ideal changeover where many of the tasks necessary to complete a changeover are converted to external tasks by completing them when the operator has idle time. After applying this method to one of the changeovers it was found that the internal time was reduced by 38%. Therefore, it has been determined that if the operator follows the method outlined in this chapter then it should be possible for the operator to convert many of the internal tasks to external ones. If the methodology cannot be followed exactly then the operator can shift certain tasks to different phases of the changeover in order to compensate for different kinds of changeovers.

CHAPTER 4 – METHOD 1: SCHEDULING JOBS IN PAIRS

The main objective of this chapter is to investigate the effects of scheduling jobs in pairs so that all of the components in a product reach the assembly area at the same time.

In most manufacturing plants, there is often an assembly operation that must be done in order to finish a product. All assembly processes involve two or more inputs that, when matched together, will form an assembly. Naturally, this matching process complicates the scheduling process greatly. The main problem with assemblies is that all of the components that make up the assembly need to be present in order for the assembly to go together. Therefore, it is often seen that plants will utilize a final assembly schedule and work backwards in order to create a schedule for the fabrication lines.

This issue has a large impact on the relationship between the assembly area and the production area which is critical to the production of any product that involves some kind of assembly. The method proposed here pairs components of the same product so that they will be processed in the production area during the same time period and delivered to the assembly area together.

This method of scheduling jobs in pairs will also decrease the overall changeover time of the product. The overall changeover time for a product is understood to be the sum of the changeover times for all of the components of a product. The method will also affect the scheduling practices in the machine shop. It will also have an effect on the inventory levels and fill rates in the assembly area.

In order to understand how the parts reach the assembly area it is important to understand how they are batched since this will affect the arrival rate of the parts. The methods for batching are defined as follows (Hopp and Spearman 2008):

- Transfer Batch – Represents the number of parts that accumulate before transferring to the next station.
- Process Batch
    - Sequential Batch – Represents the number of transfer batches that are processed before a workstation is changed over to another part or family.
    - Simultaneous Batch – Represents the number of parts produced simultaneously in a “true batch” workstation, such as a furnace or heat treatment operation.

4.1 Current State: Uneven Production

The manufacturing method being studied is unique in that it uses two different styles of batching. The machine shop (production area) at this company utilizes a transfer batch system that has a batch size that is always equal to the lot size. As the parts come off of the CNC machines they are put into crates or bins and when the job is complete they are placed in the staging area. When the forklift operator sees a buildup of finished goods he will transfer the crates and bins to their respective assembly cells. On the other hand, the assembly area utilizes a sequential batching system meaning that when one assembly is completed it is transferred to the next station. Here, the assemblies are placed on a conveyor belt that brings finished assemblies to the paint station where they are painted and then packaged.

This means that an inventory of components is stored in the assembly area and the components are used in assemblies as they are needed. Storing the inventory in the assembly area is necessary to increase fill rates and reduce lead times for finished products. Since jobs are released by customer orders, there must be some inventory in the assembly area so that demand for orders can be met. Storing inventory in the assembly area is an effective way to increase fill rates; however, the problem is complicated when components are used in multiple product assemblies.

In the case of this company, many of the components are used in multiple assemblies. The system currently utilizes one kanban card for each component (regardless of how many products the component is used in). Therefore, if one component is used in two different assemblies, then the ordering quantity is derived from the demand that is seen for the total of the two assemblies. The problem arises when there is a demand spike, or demand variability, in one assembly but not in the other. Hence, the assembly experiencing the demand spike will use up all of the components and there will be none left for the other assembly. This concept can be described more thoroughly through a theoretical example.

An example of the aforementioned problem has been presented in Figure 25. In this example there are two manufacturing lines, one that makes 12 ounce bottles and one that makes 24 ounce bottles. Both of the bottles are assembled with the same bottle caps. There is also a machine shop that “machines” the bottles and the caps. The orders from the assembly area to the machine shop are placed through kanban cards; the kanban order quantities for the 12 ounce bottles, 24 ounce bottles, and the caps are 40, 40, and 50, respectively. The orders to assemble the different bottles are placed through a customer based pull system.

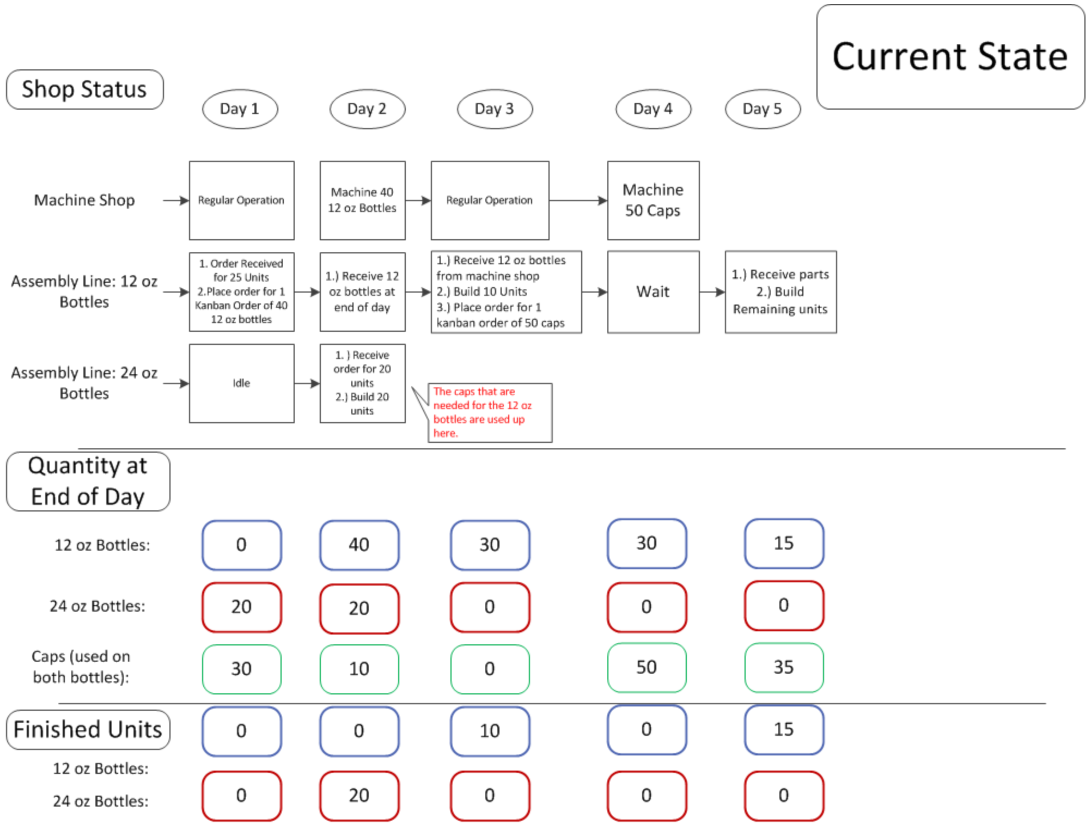


Figure 25: Current state – Uneven production

In this example assume that an order gets placed to assemble 25 of the 12 ounce bottles and to fulfill the order a kanban is sent to the machine shop to machine 40 of the 12 ounce bottles. While the machine shop is machining the 12 ounce bottles the assembly line for the 24 ounce bottles uses up all the caps. Therefore once the 12 ounce bottles arrive at the assembly area another order must be placed to machine more caps so that the original order for the 12 ounce bottles can be fulfilled.

In this example, and for the company being studied, a method called variability pooling has been used to help increase fill rates. This method pools components that are used in multiple assemblies in the same batch so that they are manufactured in larger quantities and at the same time. This way, if one product has a demand spike then there will still be some parts left for other orders. Essentially, this method relies on the fact that there is less of a chance for both assemblies to experience a demand spike at the same time. This example attempts to increase fill rates by using variability pooling; however, it has been seen that if demand variability is too high then parts can still run out. This problem can also be attributed to the fact that inventory levels are too low.

One of the reasons why this example experiences low fill rates is because the order quantity is too low and has not been adjusted for an increase in demand, or variability. If the order quantity and inventory levels are too low, then when one assembly has a demand spike the other assembly will not have any components left. Basically, if inventory levels are too low then variability pooling is no longer effective. This issue is clearly evident through this example.

Since the demand variability has caused a higher demand in one product, but not the other, it means that the components are hitting their reorder points at different times. Once this occurs then the components are produced at different times and therefore they do not arrive at the assembly area at the same time.

The problem of inconsistent arrival times is a direct violation of the assembly operations law which is defined by (Hopp and Spearman 2008):

The performance of an assembly station is degraded by increasing any of the following:

1. Number of components being assembled.
2. Variability of component arrivals.
3. Lack of coordination between component arrivals.

The issue presented here directly violates the third principle of the assembly operations law since the components do not arrive at the assembly stations at the same time. Since the caps are used in both assembly lines they can get used up in one assembly line while the other is still waiting for parts from the machine shop. This problem has a huge impact on the lead time for the finished products since assembly lines spend too much time waiting for parts.

To summarize, what has happened here is that inventory levels are too low for the demand and the variability in the demand, which has caused the components for the same product to hit their reorder points at different times. This means that production for different components happens during different time periods and therefore the components reach the assembly area at different times.

To solve this problem it is necessary to get the component arrivals synchronized so that they reach the assembly area at the same time. This means producing components for a given product with the same time period. This solution will be discussed in section 4.2.

Another way to help solve this problem is to reduce replenishment lead times. If this occurred, then the assembly line experiencing a part shortage could order the parts and receive them in enough time to meet the order deadline for the downstream customer. However, this solution is not always possible since it will most likely require an increase in capacity. Even though this is an effective solution it will not be studied in this research since scheduling and changeover reduction methods are the focus of this study.

4.2 Permanently Pairing Jobs to Even Out Production

To solve this problem it will be necessary to produce and deliver all the machined components that are used in a product at the same time. In order to accomplish this goal, all of the components for a particular product need to be produced during the same time period. Therefore, components that are used in more than one product should be processed in separate batches, with other components of the corresponding product.

Figure 26 shows how this will affect the assembly lines of the bottles. Both the caps for the 12 ounce bottles and the 24 ounce bottles will be machined in separate batches. The caps dedicated to the 12 ounce bottles will be machined when the 12 ounce bottles are machined. The same thing will be true for the 24 ounce bottles. Through the example, it is seen that the original order for the 12 ounce bottles can be finished in 3 days as opposed to the 5 days that was needed in Figure 25.

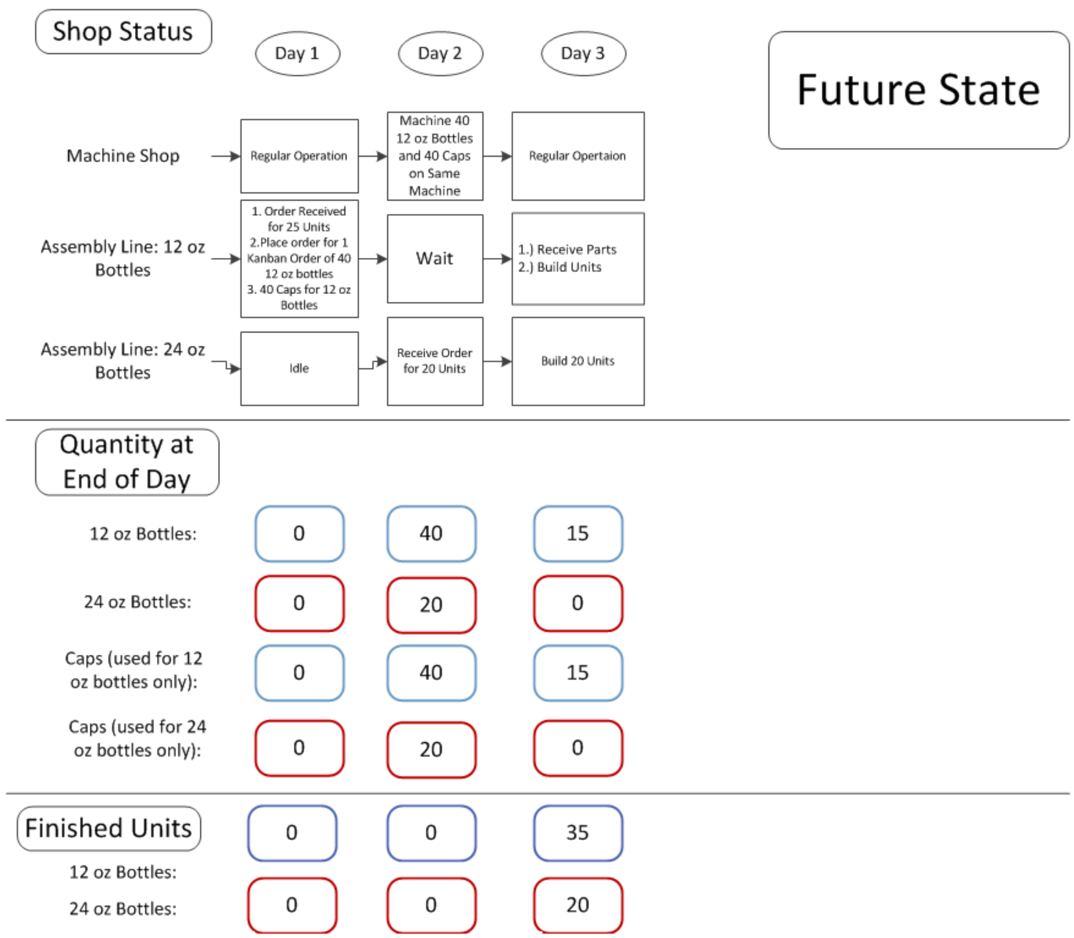


Figure 26: Future state – Even production

In the case of the company being studied, it will be necessary to machine all of the components that go into a product during the same time period. If a component is used in more than one product, then the component will be machined in separate batches with the other components that make up the product. The assembly area will be organized by product and if a component is used in two products then it will only be used with its designated product.

Since the vertical CNC machines all have two tables, it is possible to manufacture two of the components in the same time period. If there are more than two components, then the other components will go on the same machine after the first two components are finished. This means that the components will reach the assembly area within a few hours of each other as opposed to a few days or even weeks, as with the current state. In order to control the orders, the kanban cards will now represent all of the components within a product. Because the components for a particular product will have the same quantities, they will all hit the reorder point at the same time.

In order to help solve scheduling problems within the machine shop, two components within a product will be permanently married and will always be made on the same machine at the same time. This means that if there is a product with 4 components and if components 1 and 3 are paired then they will always be paired together in the future. Components 2 and 4 will also be paired and always run together as well. The advantages of permanently pairing jobs will be explained in section 4.4.

4.3 Effects on the Changeover Time

By grouping jobs in pairs the overall changeover time for the product will be reduced. The relevant theory and application will be discussed in the following sections.

4.3.1 Theory

The method of permanently pairing jobs will also have a direct effect on the changeover time. This method reduces the time that the end product will spend waiting for changeovers, therefore, reducing the lead time of the product. Currently, components of one product are being set up with components of another product, meaning both products are waiting during changeovers for components that do not belong to them. If jobs are paired, then components for product A will be set up with other components for product A.

Since components will be set up with other components that belong to the same product, they will not be waiting for components that belong to other products during the set up process. Therefore, the overall changeover time for a product will be cut in half. While this does not reduce the changeover time itself, it does reduce lead times since less time will be spent on changeovers for a particular product. The phenomenon is shown visually in Figure 27.

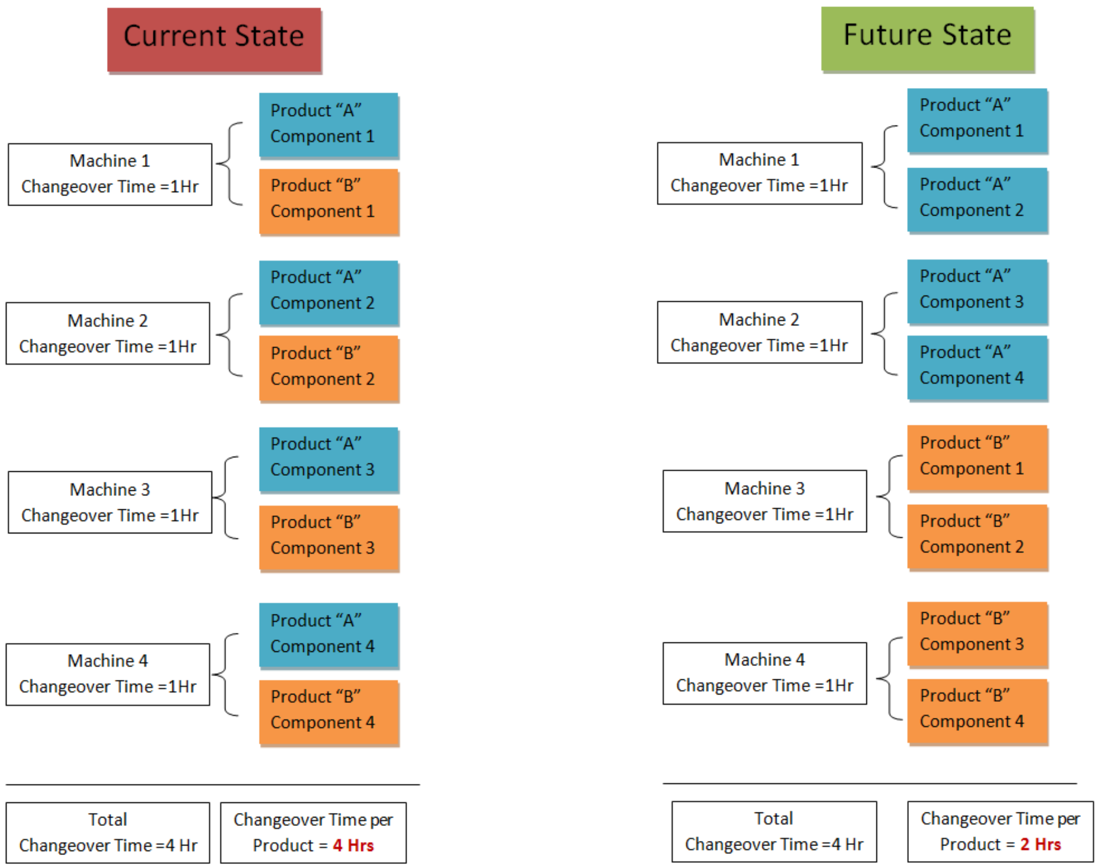


Figure 27: Job pairing

The current state of Figure 27 shows a changeover time per product of 4 hours, while the future state shows a changeover time per product of 2 hours.

As presented here, this solution seems simple; however, it is rare that all four components of a product will be machined in such close proximity of each other. It is more realistic that the components will be machined over a span of several days. This is due to the fact that individual components are manufactured when their quantities hit the reorder point. The quantities of each component within a product are rarely equal and therefore they do not hit the reorder point at the same time. This means that all four components of a product will be machined with four different components that belong to four different other products.

4.3.2 Application

This method has been applied to the most commonly made products at this company. A list has been compiled of the products that represent the top 80% of the company's profit. The list represents 74 products and 160 components. These parts have all been paired together so that the components for each product will be machined on the same machine. For products with more than two parts, they will be machined on the same machines after the preceding pair has been processed. This list can be found in Appendix III.

Through analysis of changeovers in this research it has been determined that on average a changeover takes 57 minutes and 47 seconds, as reported in chapter 3. This means that products with two components that are not machined on the same machine will spend 114.46 minutes waiting for other parts to get changed over. If these two parts are made on the same machine then the product will only wait 57.78 minutes.

Table 6 shows the time a product spends being changed over according to how many components the product has. If the product has an odd number of components then one of the components will have to be paired with a component of a different product.

Components/Product	Unpaired	Paired
1	0:57:14	0:57:14
2	1:54:28	0:57:14
3	2:51:42	1:54:28
4	3:48:56	1:54:28
5	4:46:10	2:51:42

Table 6: Changeover times seen by the product

This table has been applied to the list of the top 74 products and it has been found that, on average, paired products spend 51 minutes less than the unpaired products to get changed over. The unpaired products spend an average of 129.56 minutes being changed over and the paired units will spend an average of 78.7 minutes being changed over. This data can be found in Appendix III in the columns labeled “unpaired” and “paired”.

4.4 Effects on the Machine Shop Schedule

Scheduling jobs in pairs will have a permanent affect on the way the jobs are to be scheduled in the machine shop. In order to understand these effects, it will first be necessary to discuss the current scheduling practices at the company being studied.

4.4.1 Current Scheduling Practices

Currently, the machine shop supervisor will schedule the jobs as they are listed on the master list; however, jobs cannot simply be assigned to a machine by the order in which they appear on the list. Since the CNC machines have two pallets it is necessary to find two jobs that can be assigned to the same machine.

There are many variables that the supervisor must consider in order to develop a practical schedule for the day. Every morning, a list of jobs containing due dates, job quantity, and job time is populated and given to the machine shop supervisor. In most cases, there are several jobs that have a check mark in the "rush" column that indicates that the job is late and should be taken as the first priority. The supervisor must also keep in mind that there are four machines that are used for everyday production.

Since some of the jobs are marked as rush, the machinist will first consider job priority meaning he will try to schedule "rush" jobs first. Then, he must consider which jobs have been completed in the preceding operation and are available to be processed on the vertical CNC machines. Next is the job cycle: how long will the job take? If the job takes too long then it could tie up a machine for the entire day when higher priority jobs need to be processed.

Since the machines all have pallet changers, this means that two jobs are scheduled to each machine (one for each pallet). After a job is selected it must be paired with another job so that both pallets have jobs. This means that the overall job times need to match, the cycle times need to match (within a few minutes), the jobs need to use 12 tools or less, and the cycle changeover times need to match.

Once all of this is considered then the jobs can be placed on the daily schedule. The schedule will then be given to the head operator and he will start setting up the tools for the upcoming jobs. It is important to note that jobs will continue over from the previous day and therefore the operators are not waiting for work at the beginning of the day.

The current scheduling method is very tedious and creates many headaches for the supervisor. The problem seems to arise mainly from the fact that two jobs must be scheduled to each machine. While the pallet changers do dramatically increase the throughput of the machine shop, they also make the scheduling much more difficult.

4.4.2 Scheduling Practices with Permanently Paired Jobs

Permanently pairing jobs will make the discussed scheduling issues much easier to handle and will free up the supervisor to work on other projects.

The main scheduling improvement that will come with this method is the fact that the supervisor will not have to worry about which jobs can be paired together. Since they will already be paired, he can simply go down the list and put them on the schedule. Now the supervisor will only have to consider the rush jobs and see if the jobs are available from the previous operation.

Now it is necessary to find permanent pairs for each component that goes through the vertical CNC machines. As mentioned, it is desired to pair components that go to the same product. This means that each component for a product will get paired with other components of that product. Since there are only 1 to 6 components to a product, it is clear that not all of the components within a product will match up nicely. The flow chart in Figure 28 shows how to pair components. If none of the jobs within the component can be paired, then redesigning the component or the fixture should be considered.

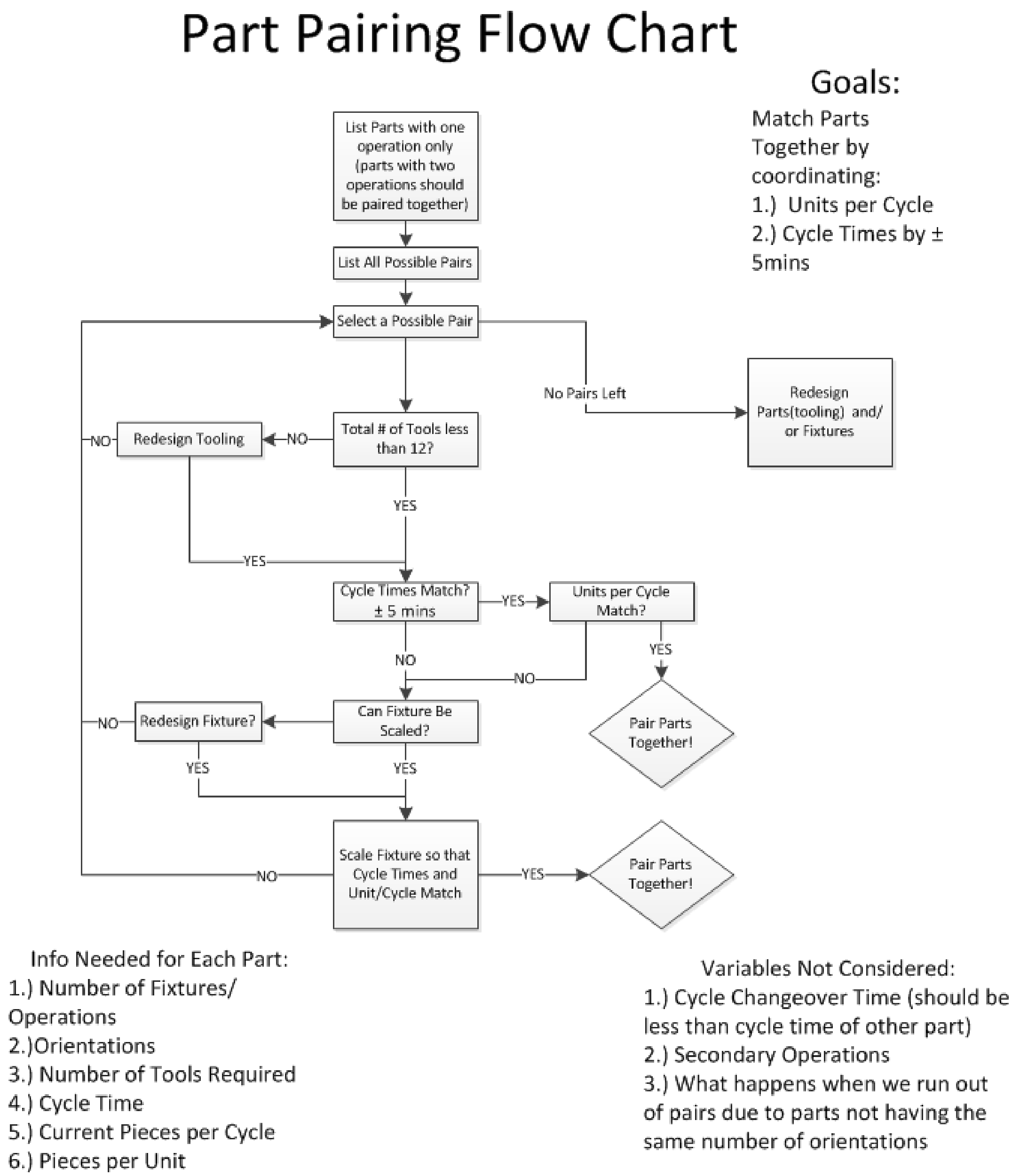


Figure 28: Part pairing flow chart

In order to have the same quantities for each component, it is necessary to have equal pieces per cycle for both jobs on a machine. To do this, the number of pieces that the fixtures can hold will need to be increased or decreased. Units per cycle will be the unit of measure used to control the quantities per cycle. When there is a product that requires more than one of the same component it will be necessary to adjust the units per cycle accordingly. In order to pair components it will be necessary to know the number of tools required, the cycle time, the pieces per cycle, and the pieces per unit. Other variables that may affect pairing are the cycle changeover times and the secondary operations. It is desired to have a cycle changeover time that is less than the cycle time of the other job in the pair.

The variables discussed have been determined for the 74 products that make up 80% of the company's profit. They have been listed in the spreadsheet in Appendix III. Due to the nature of changing the number of pieces that each fixture can hold, it will take a considerable amount of time to rewrite the CNC programs and make the necessary changes to each fixture. However, with the use of the data compiled in the spreadsheet and the company's expert knowledge of their fixtures they should be able to easily find the most effective pairings.

Once all of the components have been paired and the necessary changes to the CNC programs and the fixtures have been made, then the components will be permanently paired. This will significantly reduce the amount of time it will take to schedule the jobs each morning. This will also ensure that the same units per job will get machined and delivered to the assembly area during the same time period.

4.5 Effects on Inventory Levels and Fill Rates

In lean practices it is desired to reduce inventory levels in order to reduce the cost of holding unnecessary goods. Once the jobs are finished in the machine shop they are delivered to the assembly area and recorded as inventory until they are used in the necessary assemblies.

It is also intended that this scheduling method will help reduce inventory levels throughout the facility. There are two things at play here that may increase or decrease the overall inventory levels. First, it is expected that inventory levels will decrease because the quantities of each component that make up an assembly will be level. Meaning, as one component of a product reaches its reorder point so will all of the other components. Currently, the levels for each component are not even; therefore, when one component is almost empty another may be almost full. The difference in the two is considered as unnecessary inventory.

On the other hand, with the proposed system there will be separate bins for every component. This means that if one component is used in two different products then there will be two different bins; one for components to go into product “A” and one for components to go into product “B”. This may increase the inventory levels in the assembly area for components that are used in multiple products.

Also, since the same components will be in separate bins it will require some discipline from the assembler not to take components from the incorrect bin. It will be tempting for the assembler to fulfill an order by “stealing” parts from a bin that belongs to another product. In order to reduce this temptation it will be necessary to educate the assemblers by explaining how it is not advantageous to “steal” parts in the long run. Also, since all the components for a product should be at the same levels then when one component is empty then the other will be as well. Thus taking parts from the incorrect bins will have no benefit.

Possibly the most important effect of scheduling jobs in pairs in order for the parts to reach the assembly area at the same time is the fill rate. The fill rate is defined as the percent of time a particular component is in stock when it is needed. It is desired for the fill rate to be as close to 100% as possible. In this case, an increase in fill rates will be seen since the production rate of every component within a product will be the same. This will also dramatically decrease lead times since this will allow the assembly worker to assemble more products. This decrease in lead time is an important objective for any company as this will dramatically improve customer satisfaction.

The effect that this method has on the inventory levels, fill rates, and lead times is an excellent area of research that could be very insightful for the company being studied. However, such research is beyond the scope of this thesis since this work is mainly focused on improving changeover time.

4.6 Chapter Summary

In this chapter, it has been discovered that scheduling jobs in pairs will address several current problems. First, scheduling will be significantly easier for the machine shop supervisor when the components have been permanently paired for production. It has also been found that the changeover time per product will be reduced by an average of 54 minutes for the top 74 products. This method will also have a positive effect on inventory levels, fill rates, and lead times.

CHAPTER 5 – METHOD 2: SCHEDULING JOBS USING GROUP TECHNOLOGY

The purpose of this chapter is to investigate the effects of scheduling jobs in a way that will eliminate the need to perform certain operations of the changeover. As discussed in chapter 3, removing and attaching tools must be done while the machine is off, which uses up valuable internal time. Another important operation that must be performed during each changeover is removing and attaching the fixtures. This chapter looks at reducing the frequency with which these operations need to be completed by placing jobs with similar tooling and similar fixtures next to each other on the schedule.

It has been observed that many jobs share tools. If the total number of tools used for both jobs is less than 12 then the tools will not have to be exchanged during the changeover. Also, if two jobs share fixtures, then exchanging the fixtures will not be required.

As mentioned in the literature review, group technology is traditionally used to position machines on the manufacturing floor so that jobs do not have to travel long distances within the factory (Burbidge 1975). The method proposed in this research uses group technology to group jobs with similar tools and fixtures next to each other on the schedule so that tools or fixtures will not have to be exchanged during the changeover.

This method utilizes the rank order clustering algorithm that was originally proposed by King (1980). To apply this algorithm, the top 74 products at this manufacturing company have been divided into the three main product lines that they produce. These product lines will be referred to as product lines A, B and C.

The top 40 part numbers for each product line were taken as the sample size and analyzed using the rank order clustering algorithm. The result is a list of jobs that is ordered in such a way that minimizes tool changeovers and fixture changeovers. This list gives a schedule for each product line, which, if followed, should reduce the changeover time by the amount predicted by the computer program. In order to utilize the schedules, it is necessary to run each product line on different machines; meaning product line A will be run on machine 1, and product line B will be run on machine 2, and so on.

Each product line was evaluated for 4 different scenarios which yields a total of 12 different scenarios that have been investigated in the research. The scenarios are as follows:

1. Product Line X
    a. Tools
        i. Unpaired
        ii. Paired
    b. Fixtures
        i. Unpaired
        ii. Paired

First, each product line was evaluated to see how much time can be saved when the algorithm is applied to the tools. The unpaired scenario represents the current condition of the company's machine shop. The paired scenario represents the future condition if the company were to adopt the method of scheduling jobs by component. After the unpaired and paired scenarios for the tools were run, the fixtures were then run through the algorithm. This was then done for all three product lines.

Currently, this company processes components that are used in multiple products in the same batch. If the company were to pair the jobs by product then they will have to process components used in multiple products in separate batches. Therefore, the number of jobs for the unpaired scenarios is higher than the number of jobs for the paired scenarios.

Table 7 displays how many tools and fixtures are used in the sample size. The table also displays how many jobs were processed for the unpaired and paired scenarios. Because this method creates more jobs to be processed once the jobs are paired, it is expected that the total tool and fixture changeover times will be greater for the paired scenarios.

				Unpaired	Paired
Product Line	Products	Tools	Fixtures	Jobs	Jobs
Product Line A	23	67	26	30	40
Product Line B	13	67	22	28	39
Product Line C	10	67	26	30	38

Table 7: Products, tools, fixtures, and jobs required for each product line

5.1 Problem Formulation

Four different programs were developed and implemented as an excel macro to evaluate each of the twelve different scenarios listed in Chapter 5. Two programs were developed for the tools; one for the unpaired scenario and one for the paired scenario. Two programs were also developed to evaluate the paired and unpaired scenarios of the fixtures. The same programs can be used by the scheduler to create a daily schedule each morning for the products that need to be produced that day.

An example of how to use the algorithm implemented in the programs can be found in Groover (2008). Groover's method has been adapted to this application and was used for the research. A screen shot of the output is displayed in Figure 29.

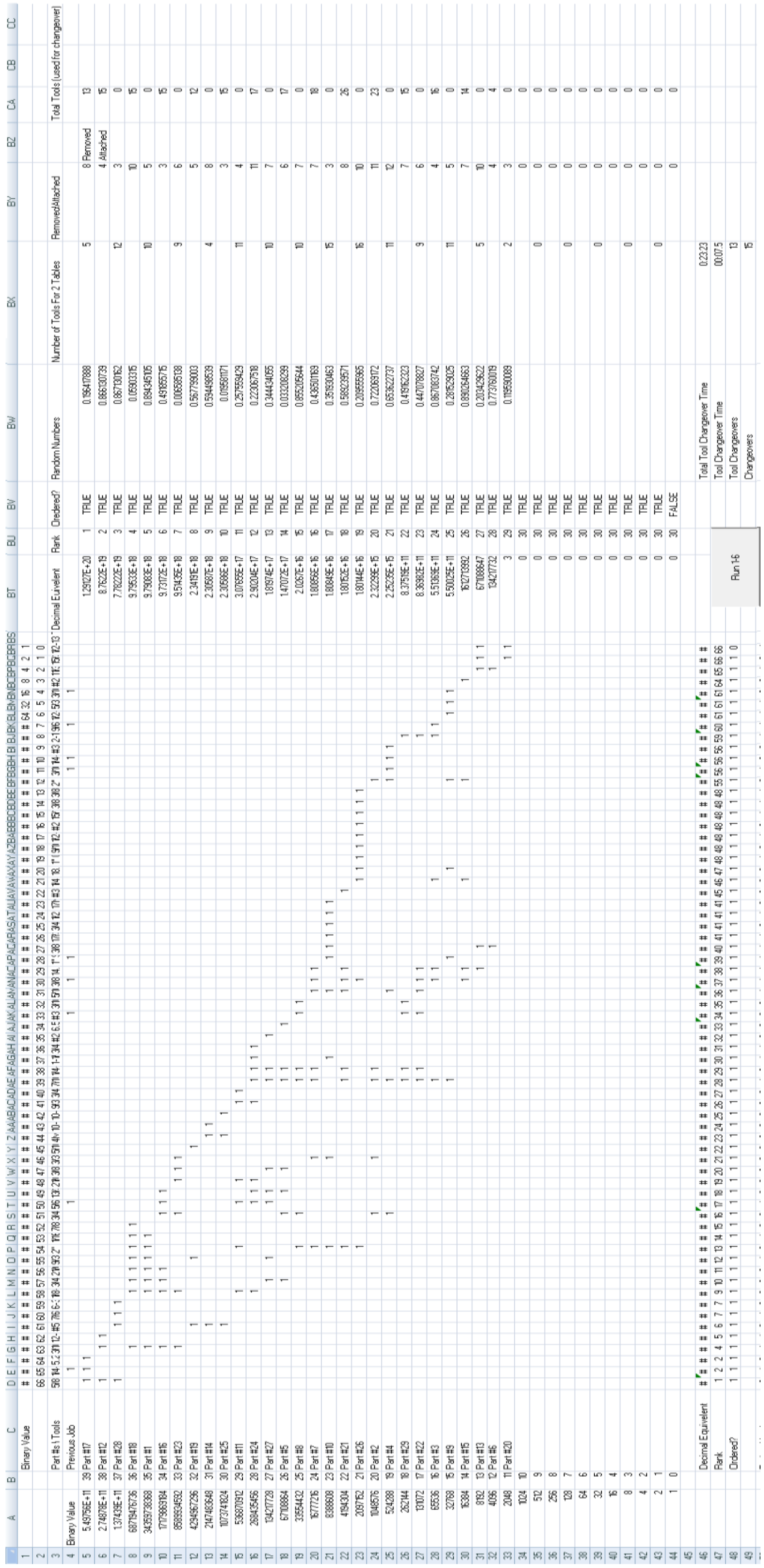


Figure 29: Program output example

Figure 29 displays the macro that optimized the tool changeover time for the unpaired components of product line A. Column C lists the part numbers for the top 40 components of product line A. Row 3 lists the tools for the corresponding part numbers. Each part number uses the tools that are designated by the "1"s in corresponding cells. The cell in column A and row 1 gives the binary value of the tools and the part numbers. The sum product is then taken for each row and column to get the decimal equivalent for each part number and tool. These results are shown in column BT for the tools, and row 46 for the part numbers. The decimal equivalents for the part numbers and tools are then ranked in the next column and row.

To start the algorithm, the part numbers and tools are randomized using the sort function on the random numbers listed in column BW and row 50. Once the algorithm is randomized, the matrix is then sorted by the rank for each tool, and then for each part number. Once the rank is sorted for the tools, then the decimal equivalent will change for the part numbers. The part numbers are then resorted according to their new ranks. The algorithm continues this process of ranking and ordering the tools and part numbers until they are both in order. Column BV and row 40 shows if the tools and part numbers are in order or not. This provides an easy visual confirmation that lets the user know if the algorithm is complete or not.

As the macro runs through the algorithm the total time required to changeover the tools is calculated in cell BX46. Cell BX47 displays the time required to changeover one tool. Cell BX48 displays how many tool changeovers are required and cell BX49 displays how many changeovers are required.

Column BY displays how many tools are required for the two tables. Since these machines utilize pallet changers it is necessary to know how many tools are needed for two jobs. The next column shows how many tools need to be removed and attached when changing from the previous two jobs. The last column shows how many tools are used between the previous two jobs and the current two jobs.

The biggest caveat of the algorithm is that the output differs slightly depending on the initial order of the part numbers and the tools. Therefore, it is necessary to run the program several times to find a local minimum for the tool changeover time. The macro runs the algorithm 12 times and places the results of each run in a cell on the spreadsheet and then copies the output to a new sheet of the workbook. Once the macro is finished, the sheet that contains the lowest tool changeover time is used as the schedule for the machine shop.

		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
	Initial Tool Changeovers	15	14	14	15	15	15	15	15	14	14	13	13	14.33333	13	15
	Initial Changeover Time	0:34:00	0:27:45	0:29:07	0:28:53	0:31:15	0:32:22	0:30:37	0:30:30	0:32:00	0:28:53	0:30:37	0:33:08	30:45.6	27:45.0	34:00.0
Minumum	Tool Changeovers	13	12	12	12	12	12	11	13	9	13	13	13	12.08333	9	13
0:23:08	Changeover Time	0:27:07	0:25:53	0:23:52	0:26:22	0:24:52	0:26:08	0:23:23	0:23:08	0:25:37	0:23:23	0:25:07	0:23:23	24:51.3	23:07.5	27:07.5
	Tool Changoever Savings	2	2	2	3	3	3	4	2	5	1	0	0	2.25	0	5
	Changeover Time Savings	0:06:53	0:01:52	0:05:15	0:02:30	0:06:22	0:06:15	0:07:15	0:07:22	0:06:23	0:05:30	0:05:30	0:09:45	05:54.4	01:52.5	09:45.0

Figure 30: Changeover times for runs 1-12 of the output displayed in figure 29

Figure 30 shows the output from the scenario in Figure 29. The first row denotes the run number. The second and third rows represent the initial number of tool changeovers and the initial changeover time. The next two rows represent the number of required tool changeovers after the algorithm was run and the optimized tool changeover time. The last two rows represent the tool changeover savings and tool changeover time savings. The average, minimum, and maximum times for each row are displayed on the right hand side of the table.

In this example, the minimum changeover time is 23.13 minutes which corresponds to run number 8. The output for run 8 can be found on sheet 8 of the spreadsheet workbook.

5.2 Tool Changeover Optimization

The first changeover operation that will be optimized is that of attaching and detaching tools. In order to minimize the tool changeover time, the aforementioned macro will be used for both the unpaired and paired scenarios for all three product lines. On average it takes 15 seconds to detach an old tool and attach a new tool. If the entire tool magazine is being changed over then the total time to change tools is 3 minutes.

The goal of this method is to arrange the jobs in an order that minimizes the number of tools that need to be loaded and unloaded. Since many of the components share tools, it is expected that there will be a reduction in changeover time when this method is applied. Product line C has 30 part numbers and uses, on average, 4.6 tools, which means that if no tools were shared then the jobs would require 138 tools. Since the 30 jobs only require 67 tools, this means that many of the tools are shared, and therefore a reduction in tool changeover time can be achieved.

Table 8 shows the results of the unpaired and paired scenarios for product line A. For the unpaired scenario the average initial time is 30.76 minutes which represents the current state of the machine shop. The optimized tool changeover time is 23.13 seconds which occurred on run 8. Therefore, if the jobs are ordered according the output of run 9 then a time savings of 7.63 minutes would be expected.

Product Line A			
Unpaired	Initial (Current State)	0:30:46	15 Changeovers
	Optimized (Method 2)	0:23:08	
	Savings	0:07:38	
	Tool Changeover Savings	2	
Paired	Initial (Method 1)	0:38:57	20 Changeovers
	Optimized (Method 1 and 2)	0:28:53	
	Savings	0:10:04	
	Tool Changeover Savings	3	

Table 8: Product line A (h:mm:ss)

Next, the paired scenario was run through the algorithm. However, due the nature of pairing jobs, the paired scenario yields results that are slightly higher than that of the unpaired scenario. In the case of product line A, the average initial tool changeover time is 38.95 minutes. The initial result of the paired scenario is representative of the tool changeover time required when the method of paired jobs is employed. The optimized tool changeover time is 28.88 minutes which is representative of using both methods 1 and 2. This yields a time savings of 7.63 minutes over 15 changeovers. The paired scenario is 5.75 minutes worse than the unpaired scenario. The time savings for the paired scenario is 10.06 minutes over 20 changeovers.

Table 9 shows the results for product line B and product line C.

Product Line B			
Unpaired	Initial (Current State)	0:29:07	14 Changeovers
	Optimized (Method 2)	0:21:15	
	Savings	0:07:52	
	Tool Changeover Savings	5	
Paired	Initial (Method 1)	0:29:02	19 Changeovers
	Optimized (Method 1 and 2)	0:22:23	
	Savings	0:06:39	
	Tool Changeover Savings	1	

Product Line C			
Unpaired	Initial (Current State)	0:28:35	15 Changeovers
	Optimized (Method 2)	0:20:45	
	Savings	0:07:50	
	Tool Changeover Savings	5	
Paired	Initial (Method 1)	0:25:51	19 Changeovers
	Optimized (Method 1 and 2)	0:23:00	
	Savings	0:02:51	
	Tool Changeover Savings	0	

Table 9: Product lines B and C (h:mm:ss)

It can be seen in Table 9 that the analysis of product lines B and C yield similar results to that of product line A. It should be noted that the tool changeover time for both product line B and product line C are slightly better than product line A. This is due to the fact that the components in product line B and C share more tools than the components in product line A.

Another way to reduce the changeover time is to reduce the number of tool changeovers that are required. For instance, suppose there is a changeover that changes from job A to job B. If job A requires eight tools and job B requires six tools then the total number of tools is fourteen. Therefore at least eight of the tools that are on the tool magazine for job A must be removed during the changeover to make room for the new tools. However, if the jobs share four tools then the total number of tools is less than twelve and a tool changeover is not necessary.

The advantage of this scenario is that the tool setting procedure will be significantly minimized. On average, a regular tool setting procedure takes 12.25 minutes. If the tools are already in the machine then the offsets do not need to be measured a second time and the offset values can be copied to the CNC programs and used for the new jobs. This process takes 6.55 minutes which saves 5.70 minutes. For example, the unpaired scenario for product line B results in five tool changeovers that do not need to be performed. This saves 28.50 minutes during the tool setting procedure.

The outputs for all the macros can be found in Appendix IV.

5.3 Fixture Changeover Optimization

The second changeover operation that is optimized is that of attaching and detaching the fixtures. On average it takes 3.08 minutes to remove one fixture and attach the next fixture. Since there are two tables per machine, this means that attaching and detaching fixtures requires 6.16 minutes per changeover.

The goal of this section is to minimize the number of fixtures that need to be attached and detached from the machines. The fixtures differ from the tools in that when a fixture is removed it is always replaced by another one. With the tools, it was necessary to find out how many tools were removed and attached because the number of tools being attached was not always the same as the number of tools being removed. Therefore, in the case of the fixtures it is only necessary to count how many fixture changeovers occur for the specified jobs.

It was found that optimizing the number of fixture changeovers yields better results than optimizing tool changeovers. Therefore, the company being studied is advised to group the jobs according to the fixtures that are used. Table 10 displays the results for all three product lines.

Product Line A			
Unpaired	Initial (Current State)	1:34:10	15 Changeovers
	Optimized (Method 2)	1:20:10	
	Savings	0:14:00	
Paired	Initial (Method 1)	1:54:05	20 Changeovers
	Optimized (Method 1 and 2)	1:23:15	
	Savings	0:30:50	

Product Line B			
Unpaired	Initial (Current State)	1:25:03	14 Changeovers
	Optimized (Method 2)	1:07:50	
	Savings	0:17:13	
Paired	Initial (Method 1)	1:44:11	19 Changeovers
	Optimized (Method 1 and 2)	1:20:10	
	Savings	0:24:01	

Product Line C			
Unpaired	Initial (Current State)	1:37:00	15 Changeovers
	Optimized (Method 2)	1:20:10	
	Savings	0:16:50	
Paired	Initial (Method 1)	1:44:11	19 Changeovers
	Optimized (Method 1 and 2)	1:23:15	
	Savings	0:20:56	

Table 10: Product lines A, B, and C (h:mm:ss)

The optimized changeover time for the unpaired and paired scenarios for product line A is 80.16 minutes and 83.16 minutes, respectively. This yields a time savings, from the current state, of 14.00 minutes for the unpaired jobs and 30.83 minutes for the paired jobs. This means that 14.00 minutes has been saved over 15 changeovers for the unpaired jobs and 30.83 minutes has been saved over 20 changeovers for the paired jobs.

The results for product lines B and C are similar to that of product line A. As expected, product line B has converged to a slightly lower time than the other product lines because product line B only has 22 fixtures, while the other two product lines each have 26 fixtures.

For every scenario, the optimized fixture changeover time yields more time savings than the optimized tool changeover times. For this reason it is advised that the company use the algorithm to optimize the fixture changeover time when creating the daily schedule. Unless the company desires, it will not be necessary to optimize the tool changeover time.

The outputs for all the macros can be found in Appendix IV.

5.4 Advantages and Disadvantages of Applying the Rank Order Clustering Algorithm

The problem discussed in this research has been applied to a real world situation that attempts to utilize an algorithm to optimize tool changeover times and fixture changeover times. Clearly, some issues will arise when attempting to apply an algorithm to a real world problem. However, it is expected that the advantages will outweigh the disadvantages. These advantages and disadvantages are discussed in the next two sections.

5.4.1 Advantages

First, this method provides a schedule for the person who is responsible for creating the daily schedule. In order to utilize the algorithm, the scheduler can select the products that need to be produced for the day and copy them into the macro. Next, the macro is run and the schedule that results in the minimum time is chosen as the schedule for that day. Currently, creating the schedule is an arduous task that takes up too much of the scheduler’s time. This method should significantly reduce the time required for the scheduler to create the daily schedule.

One of the main problems that results from scheduling the jobs in pairs is that components that are used in multiple products will now be produced in separate batches. However, when this algorithm is applied to the fixtures it will place jobs with like fixtures, and therefore like components, next to each other on the schedule. This means that only one table will need to be changed over when the same part numbers are scheduled back to back. This will offer a large changeover time reduction since only one job will need to be changed over.

It is seen that when the algorithm is used on the unpaired components of product line A, there are 26 fixture changeovers. When applied to the paired scenario, there are 27 fixture changeovers necessary for the same sample size. This means that all but one of the components used in multiple products can be scheduled next to each other on the schedule. Table 11 shows the number of fixture changeovers required for the optimized scenarios for all three product lines.

	Fixture Changeovers - Unpaired	Fixture Changeovers - Paired	Fixture Changeover Difference
Product Line A	26	27	0:03:05
Product Line B	22	26	0:12:20
Product Line C	26	27	0:03:05

Table 11: Optimized fixture changeovers

This observation is an important concept to understand because it means that the issue of having multiple changeovers for the same component is nearly nonexistent when using the method outlined in this chapter. For that reason, using group technology provides an elegant solution to the problem found by scheduling jobs in pairs.

Also, using this method will help the schedulers, engineers, and operators understand which fixtures and tools should be targeted for possible redesign opportunities. For example, if there are two jobs that often end up next to each other on the schedule because they share many of the same tools, then it might be possible to redesign the tooling so that the two jobs share more tools. The same applies for fixtures and can help employees realize which fixtures should be converted.

Lastly, and most importantly, this method provides a way to minimize the tool and fixture changeover time for a given list of part numbers. Not only can the algorithm be applied to the company's current state but it can also be applied when jobs are paired by product.

5.4.2 Disadvantages

As with any scheduling method, there are some disadvantages of scheduling jobs using group technology.

First, in order for the optimized changeover time to be accomplished, it will be necessary to schedule the jobs exactly as they are seen in the macro. This means that jobs cannot be moved around the schedule to accommodate changes in the desired schedule. For instance, if a job needs to be rushed through the shop to meet demand and is at the end of the list, it cannot be moved to the top of the list without causing increases in changeover times. Also, once the schedule is made, it will be difficult to add jobs to the schedule. Adding jobs will result in a schedule that may not be optimal and the jobs at the bottom of the list will get processed even later.

With this method, it is also necessary to create a schedule for each machine. In this research it has been understood that the three main product lines will each be designated to one machine. The disadvantage to this scenario is that when one product line sees a spike in demand then the machine may not have enough capacity to keep up with demand.

To this point, the company does not, necessarily, have to allocate the machines as was done in this research. They could opt for another strategy where the daily demand is then run through the algorithm, divided into thirds and then assigned to a machine. This will create a schedule that will have a mix of all three product lines on each machine. Also, combining all three product lines together may result in even better changeover times, as some of the components from different product lines may share similar tools and fixtures. In fact, this should be the strategy for the parts that were not in one of the three product lines researched here. This will include parts that are not made as frequently and parts that are produced for the spare parts sector of the company.

Lastly, it is necessary to discuss the low impact of this method on the tool and fixture changeover times. It is clear that a savings of 30 minutes over 20 changeovers is not a huge savings in internal time. However, the advantages of an improved daily schedule with fewer changeovers outweigh the disadvantage of the small reduction in changeover times. Therefore, it is suggested that this method by employed as a means to reduce changeover times.

5.5 Chapter Summary

The method outlined in this chapter provides a means for optimizing the time that will be spent on tool and fixture changeovers. Not only does this method minimize changeover times but it can also be used to create daily schedules for the vertical CNC machines in the machine shop.

If the company were to apply this method to their current process, then the tool changeover time will be reduced by 7.63 minutes for their most profitable product line, product line A. When this method was applied to product line A after the products had been paired, a 10.06 minute reduction in tool changeover time was seen. At 14 minutes for the unpaired products and 30.50 minutes for the paired products the reduction in fixture changeover time was found to be much higher than the reduction in tool changeover time.

This method also provides an attractive solution to the problem that came to light in chapter 4, when pairing jobs was discussed. The issue is that when components are paired by product, the components that are used in multiple products need to be produced in multiple batches. Once group technology is applied to the paired products then products with the same components will be placed next to each other on the schedule. This means that components used in multiple products can once again be processed in one batch but will only be manufactured when all the components in a product reach a common reorder point.

CHAPTER 6 – CONCLUSIONS AND FUTURE WORK

This research has explored three ways to reduce changeover times for CNC milling machines at an industrial manufacturing company. First, the SMED methodology was used to analyze the current changeover process and a new changeover methodology was proposed. Next, two methods were developed in order to solve the specific problems evident with the company being researched. The first method is to permanently pair the components of a product so that they are manufactured during the same time period. This will cause all the components for a product to reach the assembly area during the same time period. The second method was developed to place jobs with similar changeover characteristics next to each other on the schedule. This reduces the number of tool and fixture changeovers required during a given scheduling period.

This research analyzed six changeovers on pallet changing CNC milling machines. It was found that the average changeover time was 57.23 minutes; 72% of which was done internally. A new changeover methodology was developed to maximize the operators time by utilizing idle time found during cycle changeovers and trial runs. When applied to one of the analyzed changeovers it was found that the internal time was reduced by 38%. It was also found that the proposed changeover methodology can be used as a standard work sheet for all changeovers.

It was observed that if the maximum number of changeover activities are done during idle time, then only loading the tools and CNC programs will need to be done internally. On average these tasks take 5.35 minutes and this should be the target set up time for the company.

This thesis also proposed a method to schedule jobs in the machine shop so that components of the same product will be processed during the same time period. By setting up two components of the same product on one machine the overall changeover time for the product can be reduced by an average of 51 minutes. More importantly, this method processes all of the components of a product at the same time which leads to higher fill rates and reduced lead times. One disadvantage to this method is that the components used in multiple products need to be machined in separate batches.

The last method developed in this research reduces the fixture and tool changeover time by reducing the frequency with which fixtures and tools need to be changed over. Through the rank order clustering algorithm it was found that minimizing the fixture changeovers offered a large reduction in time. The programs developed in the research can be used on a daily basis to develop a schedule for the machine shop that minimizes fixture changeover time. The research also proved that this algorithm can be used to reduce the number of required changeovers by placing jobs for the same component next to each other on the schedule, thus solving the problem that arose when scheduling jobs in pairs.

Table 12 summarizes the time savings when using the proposed changeover methodology (Chapter 3) and method 2 (Chapter 5). With an average of 3 changeovers per day, it can be seen that the proposed changeover methodology will yield 48.63 days in time savings over one year. The unpaired and paired scenarios for method two yields an annual time savings of 2.48 days and 2.96 days, respectively. It is also important to note that Table 12 is for one machine and that the company being studied has four machines that are used on a daily basis, meaning the company will save approximately 200 hundred days in changeover time a year. This is clearly a very large savings and if these methods are implemented then the company should see significant results.

Time Savings per Machine			
	Proposed Changeover Methodology	Method 2 - Fixtures (unpaired)	Method 2 - Fixtures (paired)
Changeovers per day	3.00	3.00	3.00
Savings per changeover (hrs)	0.36	0.02	0.02
Daily Savings (hrs)	1.07	0.05	0.06
Weekly Savings (hrs)	5.33	0.27	0.32
Monthly Savings (hrs)	31.98	1.63	1.95
Annual Savings (hrs)	389.03	19.85	23.67
Annual Savings (days)	**48.63**	**2.48**	**2.96**
Annual Savings (weeks)	9.73	0.50	0.59

Table 12: Changeover summary

6.1 Future Work

This work offers many areas of future work that will be beneficial to academia and to the company studied in this research. First the SMED methodology should be further utilized in order to reduce the changeover times to the target time of 5.35 minutes. This can be accomplished by performing stage three of Shingo's SMED methodology which is to streamline all of aspects of the changeover. If all the activities are streamlined through work and time studies then more of the changeover activities can be done during idle time.

As mentioned, scheduling jobs in pairs will have an effect on the inventory levels, fill rates, and lead times for the company. Understanding this relationship would be another excellent area of future work. This relationship can be used to help understand the process lead time of the machine shop, which can be used to determine the optimal order points and the optimal order quantities for kanban cards.

Another area of future work for this research is to further develop the programs used in chapter 5. An area of further development could consist of combining the programs so that both the tool and fixture changeovers will be optimized on one schedule. Also, the job size and cycle times could be included on the programs so that it will be possible to determine how long a particular schedule will be valid for. Also, if the company would like to implement the existing program on all of their products then the tool and fixture data will need to be collected for the remaining part numbers.

APPENDIX I - CHANGEOVER DATA

Changeover Analysis Sheet (AB_AC)			Unique Properties: A is not getting changed over
Machine: Chiron 4	Changeover Personnel: Operator and Head Operator	Date : 12/3/2010	Tool Set up Not Filmed
Changed From:A and B	Changed To: A and C	Total Time: 1:07:22	

No.	Work Element	Finish Time	Net Time	Internal/Externa	P/M/S/T/D	Notes:
1	Start	0:00:46				
2	Remove Fixture (B)	0:01:58	0:01:12	E	M	
3	Clean With air (B)	0:02:25	0:00:27	E	M	*Machine stops at 2:24
4	Continue Removing Fixture (B)	0:02:56	0:00:31	I	M	
5	Finish Cleaning (B)	0:03:17	0:00:21	I	M	
6	Place Fixture on Cart (B)	0:03:30	0:00:13	I	M	
7	Clean Machine with Air	0:04:02	0:00:32	I	M	
8	Distraction	0:04:22	0:00:20	I	D	
9	Cycle Changeover (A)	0:09:08	0:04:46	I	P	
10	Flip Table and Start Machining (A)	0:09:19	0:00:11	I	P	
11	Grind FGs (B)	0:14:40	0:05:21	E	P	
12	Clean FGs (B)	0:15:35	0:00:55	I	P	*Machine Stops at 13:50
13	Remove FGs (Bring to Pick Up Area)	0:17:17	0:01:42	I	P	
14	Places Cardbaord in FG Crate (A)	0:17:40	0:00:23	I	P	
15	Retrieve Fixture (C)	0:18:33	0:00:53	I	P	
16	Clean Machine with Air	0:18:54	0:00:21	I	M	
17	Attach Fixture (C)	0:20:32	0:01:38	I	M	
18	Retrieve RMs (C)	0:22:20	0:01:48	I	P	
19	Organize Bins	0:22:45	0:00:25	I	P	
20	Paper Work	0:23:08	0:00:23	I	P	
21	Attach RM (C)	0:25:07	0:01:59	I	T	
22	Paper Work	0:25:40	0:00:33	I	P	
23	Remove Old Tools and Attach New Ones	0:28:05	0:02:25	I	M	* 11 Tools
24	Load CNC Programs	0:31:47	0:03:42	I	S	
25	Prove 1st orientation (C)	0:32:50	0:01:03	I	T	
26	Start	0:00:00		I		
27	Prove 1st orientation (C)	0:01:24	0:01:24	I	T	
28	Flip Table and Attach RM for 2nd Orientation (C)	0:04:55	0:03:31	I	T	
29	Flip Table, Prove (C)	0:06:48	0:01:53	I	T	
30	Cycle Changeover (A)	0:09:52	0:03:04	I	P	*Starts Removing FG(A)
31	Flip Table and Attach RMs for 3rd Orientation (C)	0:13:47	0:03:55	I	T	
32	Finsh Proving (C)	0:19:00	0:05:13	I	T	
33	Replace Bad Tool	0:20:29	0:01:29	I	S	*Tool Set up was done externally at an earlier time
34	Finish Proving	0:22:00	0:01:31	I	T	
35	Changeover Complete					
36	Set Tool Heights		0:13:18	E	S	*A is not being changed over.
41						

Changeover	E	I	% of Set up	Cum. Percent
Preperation and Aftercare	7.941613063	22.34042553	30.28203859	30.28203859
Mounting Tools and Fixtures	2.449282533	8.931222167	11.3805047	41.6625433
Measurement, Settings, and Calibrations	19.74270163	7.694210787	27.43691242	69.09945571
Trail Run	0	30.40573973	30.40573973	99.50519545
Distraction	0	0.494804552	0.494804552	100
Total	30.13359723	69.86640277	100	

Preperation and Aftercare (P)	Time	Percent	Cum. Percent
Tool Setting	0:00:00	0	0
Paper Work	0:00:56	4.575163399	4.575163399
Cleaning, Organizing	0:00:25	2.04248366	6.617647059
Retrieving Boxes, Raw Materials and Fixtures	0:04:23	21.4869281	28.10457516
Detach FG and Finish Secondary Operations	0:14:40	71.89542484	100
Total	0:20:24	100	

Main Function	Symbol	Time	Percentage	Cum. Percent
Preperation and Aftercare (P)	P	0:20:24	30.28203859	30.28203859
Mounting Tools and Fixtures (M)	M	0:07:40	11.3805047	41.6625433
Measurement, Settings, and Calibrations (S)	S	0:18:29	27.43691242	69.09945571
Trail Run (T)	T	0:20:29	30.40573973	99.50519545
Distraction (D)	D	0:00:20	0.494804552	100
Total	Total	1:07:22	100	100

Mounting Tools and Fixtures (M)	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:03:34	46.52173913	46.52173913
Cleaning	0:01:41	21.95652174	68.47826087
Removing and Attaching Tools	0:02:25	31.52173913	100
Total	0:07:40	100	

Times Used to Find Averages	Use Ave	
Setting Tool Heights	Use Ave	
Removing and Cleaning Fixture (Table 1)	N/A	
Removing and Cleaning Fixture (Table 2)		0:03:16
Attaching Fixture 1 (Table 1)	N/A	
Attaching Fixture 1 (Table 2)		0:01:59
Removing old Tools and Attaching New Ones		0:02:25
Programming		0:03:42
Proving (Table 1)		
Proving (Table 2)		0:11:04

Measurement, Settings, and Calibrations (S)	Time	Percent	Cum. Percent
Setting Tool Heights	0:13:18	71.95671776	71.95671776
Inspecting/Calibrating	0:01:29	8.025247971	79.98196573
Programing	0:03:42	20.01803427	100
Total	0:18:29	100	

Changeover Analysis Sheet (C_DE)

Machine: Chiron 4		Changeover Personnel: Operator and Head Operator			Date and Time: 12/8/2010	
Changed From:C		Changed To: D and E			Total Time: 1:02:31	
No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D	Notes:
1	Start	0:00:18				
2	Retrieve Raw Materials (D)	0:03:20	0:03:02	I	P	
3	Attach RM to Modular Fixture (D)	0:05:05	0:01:45	I	T	
4	Attach Modular Fixture to Fixture (D)	0:05:12	0:00:07	I	T	
5	Paper Work	0:05:33	0:00:21	I	P	
6	Distraction	0:06:20	0:00:47	I	D	
7	Locating Tool for Secondary Operations (Reamer) (D)	0:07:33	0:01:13	I	P	
8	Attach RM to Modular Fixture #2 and #3 (D)	0:10:49	0:03:16	I	T	
9	Organize Bins	0:11:20	0:00:31	I	P	
10	Move Tools from Cart to Machine	0:12:24	0:01:04	I	P	
11	Remove Old Tools and Attach New Ones	0:16:20	0:03:56	I	M	
12	Loading CNC Programs	0:19:00	0:02:40	I	S	
13	Prove 1st orientation (E)	0:22:30	0:03:30	I	T	
14	Flip Table and Attach RMs for 2nd Orientation (E)	0:24:00	0:01:30	I	T	
15	Prove 2nd orientation (E)	0:27:34	0:03:34	I	T	
16	Flip Table and Attach RMs for 3rd Orientation (E)	0:29:53	0:02:19	I	T	
17	Prove 3rd Orientation (E)	0:33:40	0:03:47	I	T	
18	Flip Table and Prove 1st Orientation (D)	0:39:49	0:06:09	I	T	* Attach RM for fourth orientation
19	Flip Table and Attach RMs for 2nd Orientation (D)	0:40:52	0:01:03	I	T	* Sets up Drill Press that is needed for secondary operations
20	Flip Table and Prove 2nd Orientation (D)	0:44:57	0:04:05	I	T	*Changover Complete
21	Cycle Changeover (E)					
22	Set Tool Heights		0:12:15	E	S	
23	Attach Fixture (E)		0:01:17	E	M	*Both Fixtures were installed previous to designated set up time
24	Remove Fixtures (C) Only one table was used on previus job		0:01:59	I	M	* Only one of the fixtures could have been installed externally since there was only one table was being used
25	Attach Fixture (D)		0:01:17	I	M	* The times used here are averages of previous set ups

Unique Properties:
Only 1 Table was being used for the previous jobs
Tool Set up Not Filmed
Trial run is long. Makes internal time look skewed

Changeover				
	E	I	% of Set up	Cum. Percent
Preperation and Aftercare	0	10.06238134	10.06238134	10.06238134
Mounting Tools and Fixtures	2.088418769	11.71684296	13.80526173	23.86764307
Measurement, Settings, and Calibrations	19.93490643	4.339571467	24.2744779	48.14212097
Trail Run	0	50.58312992	50.58312992	98.72525088
Distraction	0	1.274749119	1.274749119	100
Total	22.0233252	77.9766748	100	

Preperattion and Aftercare (P)			
	Time	Percent	Cum. Percent
Tool Setting	0:01:13	19.67654987	19.67654987
Paper Work	0:00:21	5.660377358	25.33692722
Cleaning, Organizing	0:01:35	25.606469	50.94339623
Retrieving Boxes and Raw Materials	0:03:02	49.05660377	100
Total	0:06:11	100	

Main Function	Symbol	Time	Percentage	
Preperation and Aftercare (P)	P	0:06:11	10.06238	10.06238
Mounting Tools and Fixtures (M)	M	0:08:29	13.80526	23.86764
Measurement, Settings, and Calibrations (S)	S	0:14:55	24.27448	48.14212
Trail Run (T)	T	0:31:05	50.58313	98.72525
Distraction (D)	D	0:00:47	1.274749	100
Total	Total	1:01:27	100	100

Mounting Tools and Fixtures (M)			
	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:04:33	53.6345776	53.6345776
Cleaning	0:00:00	0	53.6345776
Removing and Attaching Tools	0:03:56	46.3654224	100
Total	0:08:29		

Times Used to Find Averages	
Setting Tool Heights	N/A
Removing and Cleaning Fixture (Table 1)	N/A
Removing and Cleaning Fixture (Table 2)	N/A
Attaching Fixture 1 (Table 1)	N/A
Attaching Fixture 1 (Table 2)	N/A
Removing old Tools and Attaching New Ones	0:03:56
Programming	0:02:40
Proving (Table 1)	0:10:51
Proving (Table 2)	0:10:14

Measurement, Settings, and Calibrations (S)			
	Time	Percent	Cum. Percent
Setting Tool Heights	0:12:15	82.12290503	82.12290503
Inspecting	0:00:00	0	82.12290503
Programing	0:02:40	17.87709497	100
Total	0:14:55		

Changeover Analysis Sheet (FG_HI)

Machine: Chiron 4		Changeover Personnel: Operator and Head Operator		Date and Time: 12/10/2010		
Changed From:F and G		Changed To: H and I		Total Time: 31:39		

Unique Properties:
No Tool Changeover(Still need to copy offsets)
F and H share fixtures

No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D	Notes:
1	Start	0:00:00				*No new tools are needed
2	Open Program Files	0:00:35	0:00:35	E	P	
3	Copy Tool Heights from Previous Jobs	0:02:36	0:02:01	E	S	
4	Distraction	0:03:05	0:00:29	E	D	
5	Continue Coping Tool Heights from Previous Jobs	0:05:48	0:02:43	E	S	
6	Post Set up Sheets	0:05:55	0:00:07	E	P	
7	Distraction	0:06:33	0:00:38	E	D	
8	Post Set up Sheets	0:07:20	0:00:47	E	P	
9	Remove Cart	0:07:40	0:00:20	E	P	
10	Start	0:10:35				
11	Pull Cart Over	0:10:44	0:00:09	I	P	
12	Clean with Air	0:10:49	0:00:05	I	M	
13	Retrieve MO	0:11:15	0:00:26	I	P	
14	Attach Work Pieces (H)	0:11:50	0:00:35	I	T	*Fixture for F and H are the same.
15	Table Flip	0:12:05	0:00:15	I	T	
16	Remove G Fixture	0:12:35	0:00:30	I	M	
17	Distraction	0:12:49	0:00:14	I	D	
18	Remove G Fixture	0:12:58	0:00:09	I	M	
19	Clean with Air	0:13:45	0:00:47		M	
20	Return Old Fixture and Retrieve New Fixture and RMs (H and I)	0:15:20	0:01:35	I	P	
21	Attach Fixture (I)	0:16:08	0:00:48	I	M	
22	Attach Raw MTLS (I)	0:16:58	0:00:50	I	T	
23	Return Set up Cart	0:17:20	0:00:22	I	P	
24	Position Raw Material Crates	0:17:40	0:00:20	I	P	
25	Retrieve Finished Good Bins	0:18:03	0:00:23	I	P	
26	Prep New Programs	0:19:40	0:01:37	I	S	
27	Prove (H)	0:25:42	0:06:02	I	T	
28	Prove (I)	0:26:12	0:00:30	I	T	
29	Cycle Changeover (H) (Still Proving I)	0:28:30	0:02:18	I	T	
30	Proving (write new jobs on white board)	0:33:03	0:04:33	I	T	
31	Cycle Changeover (I) (close door)	0:34:34	0:01:31	I	T	*Changeover complete
32	Clean with Air	0:35:15	0:00:41			
33						

Percent External and Internal

	E	I	% of Set up	Cum. Percent
Preperation and Aftercare (P)	5.739863086	10.2685624	16.00842549	16.00842549
Mounting Tools and Fixtures (M)	0	7.319641917	7.319641917	23.3280674
Measurement, Settings, and Calibrations (S)	14.9552396	5.107951553	20.06319115	43.39125856
Trail Run (T)	0	52.3433386	52.3433386	95.73459716
Distraction (D)	3.528172722	0.74	4.265402844	100
Total	24.22327541	75.77672459	100	100

Preperation and Aftercare (P)

	Time	Percent	Cum. Percent
Tool Setting	0:00:55	18.09210526	18.09210526
Paper Work	0:01:20	26.31578947	44.40789474
Cleaning, Organizing	0:00:31	10.19736842	54.60526316
Retrieving Boxes, Raw Materials, and Fixtures	0:02:18	45.39473684	100
Total	0:05:04	100	

Mounting Tools and Fixtures (M)

	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:01:27	62.58992806	62.58992806
Cleaning	0:00:52	37.41007194	100
Removing and Attaching Tools	0:00:00	0	100
Total			

Measurement, Settings, and Calibrations (S)

	Time	Percent	Cum. Percent
Setting Tool Heights	0:04:44	74.54068241	74.54068241
Inspecting	0:00:00	0	74.54068241
Loading Programs	0:01:37	25.45931759	100
Total		100	

Main Function	Symbol	Time	Percent	Cum. Percent
Preperation and Aftercare (P)	P	0:05:04	16.00842549	16.00842549
Mounting Tools and Fixtures (M)	M	0:02:19	7.319641917	23.3280674
Measurement, Settings, and Calibrations (S)	S	0:06:21	20.06319115	43.39125856
Trail Run (T)	T	0:16:34	52.3433386	95.73459716
Distraction (D)	D	0:01:21	4.265402844	100
Total	Total	0:31:39	100	

Times Used to Find Averages

Setting Tool Heights	0:07:40
Removing and Cleaning Fixture (Table 1)	N/A
Removing and Cleaning Fixture (Table 2)	0:01:26
Attaching Fixture 1 (Table 1)	
Attaching Fixture 1 (Table 2)	0:00:48
Removing old Tools and Attaching New Ones	N/A
Programming	0:01:37
Proving (Table 1)	0:06:02
Proving (Table 2)	0:07:21

Changeover Analysis Sheet (JK_LM)						Unique Properties: *Fixture K removed previous to changeover
Machine: Chiron 4	Changeover Personnel: Operator and Head Operator			Date: 12/21/2010		
Changed From:J and K	Changed To: L and M			Total Time: 1:09:27		
No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D	Notes:
1	Start	0:00:00				
2	Pull Cart Over	0:00:15	0:00:15	E	P	
3	Open Programs and Delete Old Offsets	0:02:00	0:01:45	E	S	
4	Prep Programs	0:04:03	0:02:03	E	P	
5	Set Tool Heights	0:08:36	0:04:33	E	S	
6	Close Programs	0:08:50	0:00:14	E	S	
7	Print and Retrieve Set up Sheets	0:09:26	0:00:36	E	P	
8	Place old Tools in Cart	0:09:57	0:00:31	E	P	
9	Double Check Offset Values	0:10:50	0:00:53	E	S	
10	Place Sheets on Set up Cart	0:11:05	0:00:15	E	S	
11	Paperwork, Disconnect Cart	0:12:20	0:01:15	E	P	
12	Start	0:14:08				
13	Remove Fixture (J)	0:15:50	0:01:42	I	M	
14	Distraction	0:16:28	0:00:38	I	D	
15	Clean Fixture	0:17:15	0:00:47	I	M	
16	Clean Table	0:17:55	0:00:40	I	M	
17	Organize Carts	0:18:25	0:00:30	I	P	
18	Paperwork	0:18:44	0:00:19	I	P	
19	Bring FGs to Pickup Area	0:19:24	0:00:40	I	P	
20	Sweep	0:21:58	0:02:34	I	P	
21	Return Old Fixture and Get New Fixture (L)	0:23:59	0:02:01	I	M	
22	Attach Fixture (L)	0:25:21	0:01:22	I	M	
23	Get RMs (L)	0:26:30	0:01:09	I	P	
24	Get FGs Boxes	0:27:12	0:00:42	I	P	
25	Attach RMs (L)	0:28:35	0:01:23	I	T	
26	Flip Table	0:29:00	0:00:25	I	M	
27	Attach Fixture (M)	0:30:48	0:01:48	I	M	
28	Get RM (M)	0:34:55	0:04:07	I	P	*Also returns RM crate to pick up area
29	Attach RM (M)	0:36:34	0:01:39	I	T	
30	Place Set up Sheet on Machine	0:37:06	0:00:32	I	P	
31	Remove Old Tools and Attach New Ones	0:38:50	0:01:44	I	M	*5 Tools
32	Prepare Programs	0:42:44	0:03:54	I	S	
33	Prove Tool Path (L)	0:53:24	0:10:40	I	T	* Get FG bin while proving
34	Flip Table, Prove (M 1st Orientation)	0:55:45	0:02:21	I	T	
35	Attach RMs to fixture (M)	0:58:50	0:03:05	I	T	
36	Flip Table, Prove (M 2nd Orientation)	1:03:02	0:04:12	I	T	
37	Inspect (L)	1:08:04	0:05:02	I	S	
38	Attach RM (L)	1:09:49	0:01:45	E	T	
39	Remove FGs (M) Changeover complete	1:11:15	0:01:26	E	T	
40	Flip Table, Cylce Changeover (M) (Changeover complete)	1:14:45	0:03:30			
41	Clean L from previous cycle (Changeover complete)	1:15:39	0:00:54			
41	Wait for M to finish (Changeover complete)	1:19:32	0:03:53			

Changeover				
	E	I	% of Set up	Cum. Percent
Preperation and Aftercare (P)	6.719462443	15.19078474	21.91024718	21.91024718
Mounting Tools and Fixtures (M)	0	15.09479242	15.09479242	37.0050396
Measurement, Settings, and Calibrations (S)	11.03911687	12.86297096	23.90208783	60.90712743
Trail Run (T)	0	38.18094552	38.18094552	99.08807295
Distraction (D)	0	0.911927046	0.911927046	100
Total	17.75857931	82.24142069	100	

Preperattion and Aftercare (P)			
	Time	Percent	Cum. Percent
Tool Setting/Loading Programs	0:04:40	30.66812705	30.66812705
Paper Work	0:00:51	5.585980285	36.25410734
Cleaning, Organizing	0:03:04	20.15334064	56.40744797
Retrieving Boxes and Raw Materials	0:06:38	43.59255203	100
Total	0:15:13	100	

Main Function	Symbol	Time	Percent	Cum Percent
Preperation and Aftercare (P)	P	0:15:13	21.91024718	21.91024718
Mounting Tools and Fixtures (M)	M	0:10:29	15.09479242	37.0050396
Measurement, Settings, and Calibrations (S)	S	0:16:36	23.90208783	60.90712743
Trail Run (T)	T	0:26:31	38.18094552	99.08807295
Distraction (D)	D	0:00:38	0.911927046	100
Total	Total	1:09:27	100	100

Mounting Tools and Fixtures (M)			
	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:07:18	69.63434022	69.63434022
Cleaning	0:01:27	13.83147854	83.46581876
Removing and Attaching Tools	0:01:44	16.53418124	100
Total	0:10:29		

Times Used to Find Averages	
Setting Tool Heights	0:12:20
Removing and Cleaning Fixture (Table 1)	0:03:09
Removing and Cleaning Fixture (Table 2)	
Attaching Fixture 1 (Table 1)	0:01:22
Attaching Fixture 1 (Table 2)	0:01:48
Removing old Tools and Attaching New Ones	0:01:44
Programming	0:03:54
Proving (Table 1)	0:10:40
Proving (Table 2)	0:06:33

Measurement, Settings, and Calibrations (S)			
	Time	Percent	Cum. Percent
Setting Tool Heights	0:07:40	46.18473896	46.18473896
Inspecting	0:05:02	30.32128514	76.5060241
Programing	0:03:54	23.4939759	100
Total	0:16:36		

Changeover Analysis Sheet (N1N2_O)

Machine: Chiron 5 | Changeover Personnel: Operator and Head Operator | Date and Time: 10/21/2010 9:0

Changed From: N-1 and N-2 | Changed To: O | Total Time: 58:06

Unique Properties:
Table 2 is blank since O uses 10 Tools
Part N has two operations (requires both tables)
Trial Run Not Filmed (Used Average)
Notes:

No.	Work Element	Finish Time	Net Time	Internal/External	Name
1	Start	0:04:12			P/M/S/T/D
2	Move Set up cart	0:04:27	0:00:15	E	P
3	Turn on computer/open word and excell	0:05:08	0:00:41	E	P
4	Find Programs open Notepad	0:05:25	0:00:17	E	P
5	Delete old offsets	0:05:48	0:00:23	E	S
6	Paper work	0:08:06	0:02:18	E	P
7	Ran out of Tool Holders	0:12:54	0:04:48	E	S
8	Set Tool Heights	0:14:25	0:01:31	E	S
9	Put tool back in cart/ disconnect	0:15:00	0:00:35	E	P
10	Prepare set up sheet	0:15:21	0:00:21	E	P
11	Retrieve Set up Sheet	0:15:40	0:00:19	E	P
12	Double Check Numbers	0:17:04	0:01:24	E	S
13	Placed Set up Sheet machine set up cart	0:17:16	0:00:12	E	P
14	Move Set up cart to original location	0:17:33	0:00:17	E	P
15	Start	0:00:00			
16	Remove Fixture (N-1)	0:00:07	0:00:07	E	M
17	Clean Fixture (N-1)	0:00:17	0:00:10	E	M
18	Turn cart around	0:00:23	0:00:06	E	P
19	Clean machine with Water and Air	0:00:56	0:00:33	E	M
20	Fasten New Fixture (O)	0:02:16	0:01:20	E	M
21	Finish Cleaning Cart/Placing Cone on Top	0:02:34	0:00:18	E	M
22	Visual Check /Close Doors	0:02:45	0:00:11	E	P
23	Start	0:00:00			
24	Remove and Clean Finished Parts (N-2)	0:00:37	0:00:37	I	P
25	Assemble Grease Fitting to Parts (N-2)	0:01:27	0:00:50	I	P
26	Place Pieces of Fixture on Fixture Cart	0:01:41	0:00:14	I	P
27	Remove FG and Return to Machine (N-2))	0:02:13	0:00:32	I	P
28	Clean machine with Water and Air	0:02:31	0:00:18	I	M
29	Mov cart to machine	0:02:53	0:00:22	I	P
30	Remove Fixture (N-2)	0:04:04	0:01:11	I	M
31	Clean Fixture (N-2). Place fixture pieces on fixture	0:04:50	0:00:46	I	M
32	Remove Fixture Cart and Replace with RM (O)	0:05:04	0:00:14	I	P
33	Retrieve Bins for FG (O)	0:05:27	0:00:23	I	P
34	Move unnecessary carts	0:05:45	0:00:18	I	P
35	Clean Table with Water and Air	0:06:09	0:00:24	I	P
36	Remove locktight from area	0:06:45	0:00:36	I	P
37	Exchange Set Up Sheets	0:06:55	0:00:10	I	P
38	Clean Tool Magazine with air	0:07:43	0:00:48	I	M
39	Remove Old tools and Instert New Ones	0:11:00	0:03:17	I	M
40	Misc. Programing	0:12:40	0:01:40	I	S
41	Send Program From PC to Machine	0:13:32	0:00:52	I	S
	Trial (average from other changeovers)		0:23:40		
		Total	0:53:18		

	E	I	% of Set Up	Cum. Percent
Preperation and Aftercare (P)	10.38148843	8.75547217	19.1369606	19.1369606
Mounting Tools and Fixtures (M)	4.627892433	11.88242652	16.51031895	35.64727955
Measurement, Settings, and Calibrations (S)	15.19699812	4.752970607	19.94996873	55.59724828
Trial (T)	0	44.40275172	44.40275172	100
Distractions (D)	0	0	0	
Total	30.20637899	69.79362101	100	

Preperation and Aftercare (P)			
	Time	Percent	Cum. Percent
Tool Setting	0:02:05	20.4248366	20.4248366
Paper Work	0:03:20	32.67973856	53.10457516
Cleaning, Organizing	0:02:11	21.40522876	74.50980392
Retrieving Boxes and Raw Materials	0:00:23	3.758169935	78.26797386
Detach FG and Finish Secondary Operations	0:02:13	21.73202614	100
Total	0:10:12	100	

Main Function	Symbol	Time	Percent	Cum. Percent
Preperation and Aftercare	P	0:10:12	19.13696	19.1369606
Mounting Tools and Fixtures	M	0:08:48	16.51032	35.64727955
Measurement, Settings, and Calibrations	S	0:10:38	19.94997	55.59724828
Trial	T	0:23:40	44.40275	100
Distractions	D	0:00:00	0	100
Total	Total	0:53:18	100	

Mounting Tools and Fixtures (M)			
	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:02:38	29.92424242	29.92424242
Cleaning	0:02:53	32.76515152	62.68939394
Removing and Attaching Tools	0:03:17	37.31060606	100
Total	0:08:48	100	

Times Used to Find Averages	
Setting Tool Heights	0:13:21
Removing and Cleaning Fixture (Table 1)	0:00:56
Removing and Cleaning Fixture (Table 2)	0:02:19
Attaching Fixture 1 (Table 1)	0:01:20
Attaching Fixture 1 (Table 2)	N/A
Removing old Tools and Attaching New Ones	0:03:17
Programming	0:02:32
Proving (Table 1)	N/A
Proving (Table 2)	N/A

Measurement, Settings, and Calibrations (S)			
	Time	Percent	Cum. Percent
Setting Tool Heights	0:07:43	72.57053292	72.57053292
Inspecting	0:00:00	0	72.57053292
Loading Programs	0:02:55	27.42946708	100
Total	0:10:38	100	

Changeover Analysis Sheet (PQ_RL)

Unique Properties
Fixture for Part Q was removed externally
Trial Not Flimed
Notes:

Machine: Chiron 5	Changeover Personnel: Operator and Head Operator	Date and Time: 10/21/2010 1:0
Changed From: P and Q	Changed To: R and L	Total Time: 52:35

No.	Work Element	Finish Time	Net Time	Internal/External	P/M/S/T/D
1	Start	0:00:00			
2	Turn on Computer and Programs	0:01:03	0:01:03	E	P
3	Gather Tools from Cart	0:01:20	0:00:17	E	P
4	Set Tool Heights	0:11:15	0:09:55	E	S
5	Remove Old Tools From Holders	0:11:35	0:00:20	E	P
6	Put Tools Back in Cart	0:12:31	0:00:56	E	P
7	Prepare and Print Set Up Sheets	0:13:22	0:00:51	E	P
8	Retrieve Set Up Sheets From Printer	0:13:41	0:00:19	E	P
9	Check Offset Values	0:15:36	0:01:55	E	S
10	Disconnect Cart	0:15:40	0:00:04	E	P
11	Start	0:00:00			
12	Remove and Clean Fixture (P)	0:00:49	0:00:49	E	M
13	Remove Old Raw Materials Bin	0:02:20	0:01:31	E	P
14	Return old Fixture and Retrieve New One	0:02:47	0:00:27	I	P
15	Install New Fixture (R)	0:03:40	0:00:53	I	M
16	Retrieve Raw Materials (R)	0:04:31	0:00:51	I	P
17	Attach New Work Pieces (R)	0:06:12	0:01:41	I	P
18	Clean Table	0:06:34	0:00:22	I	M
19	Install New Fixture (L)	0:07:25	0:00:51	I	M
20	Retrieve Raw Materials (L)	0:08:46	0:01:21	I	P
21	Attach New Work Piece (R)	0:09:32	0:00:46	I	P
22	Bring over FGs Bins	0:10:00	0:00:28		P
23	Remove Old Tools and Insert New Ones	0:11:53	0:01:53	I	M
24	Misc. Programming	0:12:24	0:00:31	I	S
25	Send Program From PC to Machine	0:13:15	0:00:51	I	S
26	Trial (Averages from other changeovers)		0:23:40	I	T

	E	I	% of Set up	Cum. Percent
Preperation and Aftercare (P)	10.17432647	10.58637084	20.76069731	20.76069731
Mounting Tools and Fixtures (M)	1.553090333	7.575277338	9.12836767	29.88906498
Measurement, Settings, and Calibrations (S)	22.50396197	2.599049128	25.10301109	54.99207607
Trial (T)	0	45.00792393	45.00792393	100
Distractions (D)	0	0	0	100
Total	34.23137876	65.76862124	100	

Preperattion and Aftercare (P)			
	Time	Percent	Cum. Percent
Tool Setting	0:01:44	15.8778626	15.8778626
Paper Work	0:01:10	10.6870229	26.5648855
Cleaning, Organizing	0:00:56	8.549618321	35.11450382
Retrieving Boxes and Raw Materials	0:04:38	42.44274809	77.55725191
Attach RM	0:02:27	22.44274809	100
Total	0:10:55	100	100

Main Function	Symbol	Time	Percentage	Cum. Percent
Preperation and Aftercare	P	0:10:55	20.76069731	20.76069731
Mounting Tools and Fixtures	M	0:04:48	9.12836767	29.88906498
Measurement, Settings, and Calibrations	S	0:13:12	25.10301109	54.99207607
Trial	T	0:23:40	45.00792393	100
Distractions	D	0:00:00	0	100
Total	Total	0:52:35	100	

Mounting Tools and Fixtures (M)			
	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:02:33	53.125	53.125
Cleaning	0:00:22	7.638888889	60.76388889
Removing and Attaching Tools	0:01:53	39.23611111	100
Total	0.003333333	100	

Times Used to Find Averages		
Setting Tool Heights		0:15:40
Removing and Cleaning Fixture (Table 1)		0:00:49
Removing and Cleaning Fixture (Table 2)	N/A	
Attaching Fixture 1 (Table 1)		0:00:53
Attaching Fixture 1 (Table 2)		0:00:51
Removing old Tools and Attaching New Ones		0:01:53
Programming		0:01:22
Proving (Table 1)	N/A	
Proving (Table 2)	N/A	

Measurement, Settings, and Calibrations (S)			
	Time	Percent	Cum. Percent
Setting Tool Heights	0:11:50	89.64646465	89.64646465
Inspecting	0:00:00	0	89.64646465
Loading Programs	0:01:22	10.35353535	100
Total	0:13:12	100	

Averages - Overall			
	Time	Percent	Cum. Percent
Preperation and Aftercare (P)	0:11:37	20.29776856	20.29776856
Mounting Tools and Fixtures (M)	0:07:06	12.39610256	32.69387111
Measurements, Settings, and Calibrations (S)	0:14:20	25.05551309	57.7493842
Trail Run (T)	0:23:40	41.34784561	99.09722981
Distractions (D)	0:00:31	0.902770194	100
Total	0:57:14	100	

Averages - Preperation and Aftercare (P)			
	Time	Percent	Cum. Percent
Tool Setting	0:01:46	15.23194644	15.23194644
Paper Work	0:01:29	12.76901004	28.00095648
Cleaning, Organizing	0:01:27	12.482066	40.48302248
Retrieving Boxes and Raw Materials	0:03:41	31.77905308	72.26207556
Finish Operations From Previous Job	0:03:13	27.73792444	100
Total	0:11:37	100	

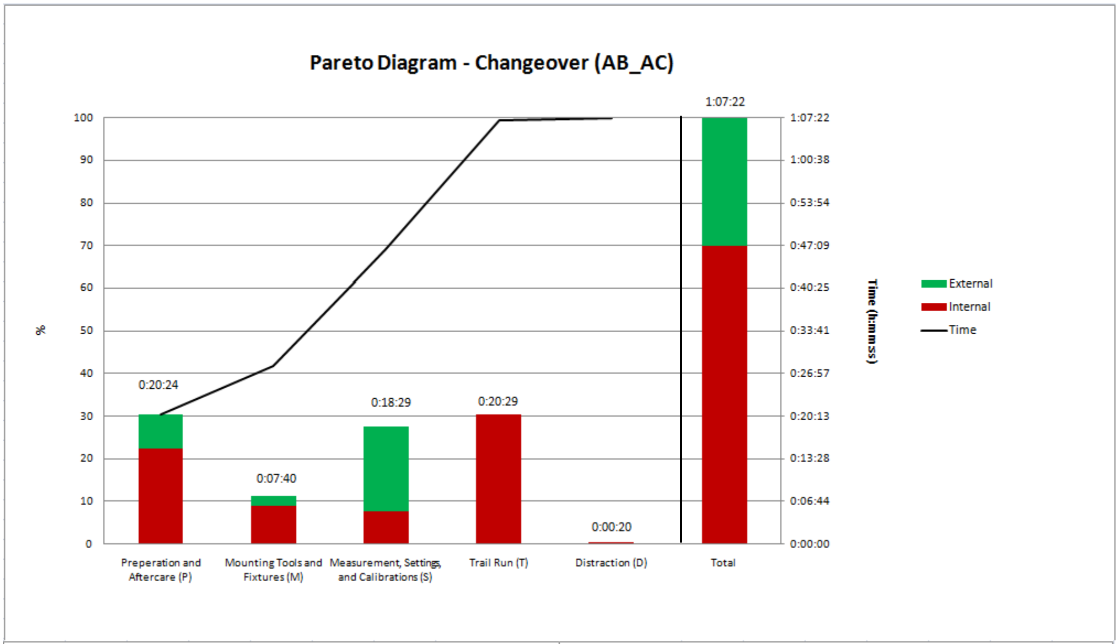
Averages - Mounting Tools and Fixtures (M)			
	Time	Percent	Cum. Percent
Removing and Attaching Fixtures	0:03:41	51.84025059	51.84025059
Cleaning	0:01:12	17.0321065	68.87235709
Removing and Attaching Tools	0:02:12	31.12764291	100
Total	0:07:06	100	

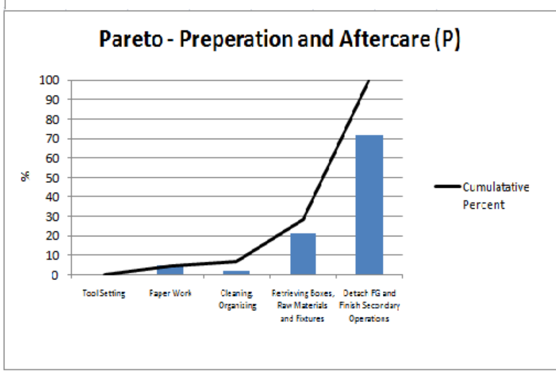
Averages - Measurement, Settings, and Calibrations (S)			
	Time	Percent	Cum. Percent
Setting Tool Heights	0:08:21	68.81480209	68.81480209
Inspecting and Calibrating	0:01:05	8.959156785	77.77395887
Programing	0:02:42	22.22604113	100
Total	0:12:07	100	

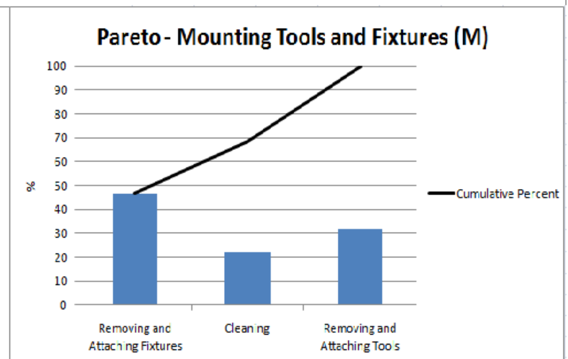
Main Function	E	I	% of Set up	Time	Cum. Percent
Preperation and Aftercare	6.921168169	13.04848085	19.96964902	0:11:37	19.96964902
Mounting Tools and Fixtures	1.706694571	10.18148716	11.88818173	0:07:06	31.85783076
Measurements, Settings, and Calibrations	18.49500267	6.120171725	24.61517521	0:14:20	56.47300596
Trail Run	0	42.38998876	42.38998876	0:23:40	98.86299472
Distractions	0.573826653	0.563178626	1.137005279	0:00:31	100
Total	27.69669287	72.30330713	100	0:57:14	

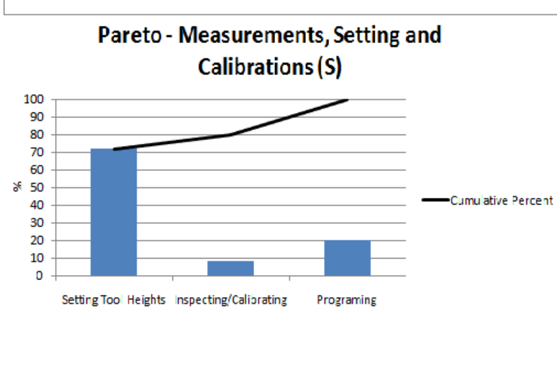
Averages of Important Elements		
Elements	Time	Percent
Setting Tool Heights	0:12:15	21.41167049
Removing and Cleaning Fixtures (2)	0:03:58	6.940652567
Attaching Fixtures (2)	0:02:35	4.501370276
Removing Old Tools and Attaching New Ones	0:02:39	4.630337447
Programming	0:02:42	4.707995098
Proving (2 jobs)	0:17:56	31.32654176

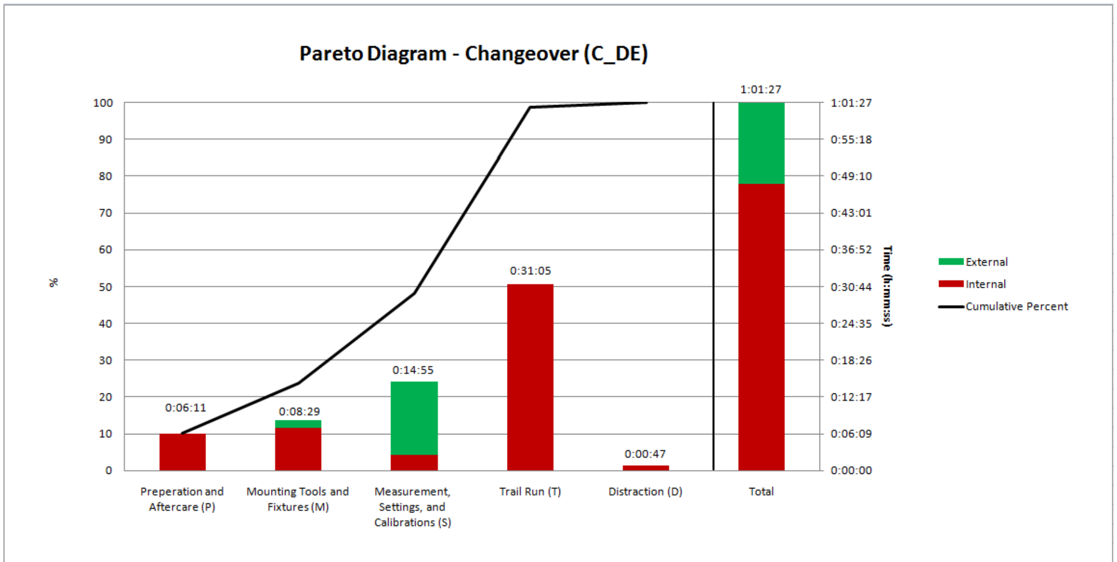
APPENDIX II - PARETO DIAGRAMS



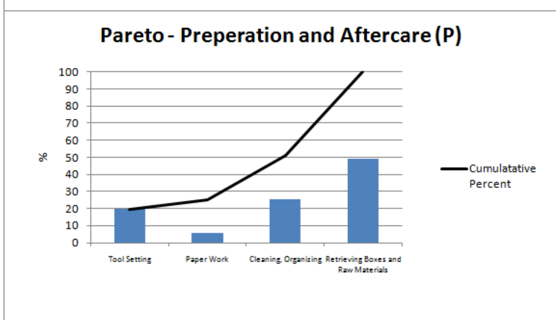




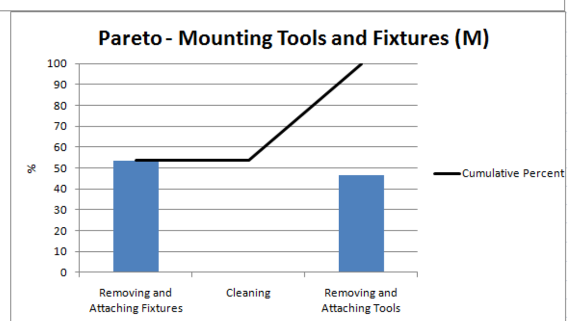




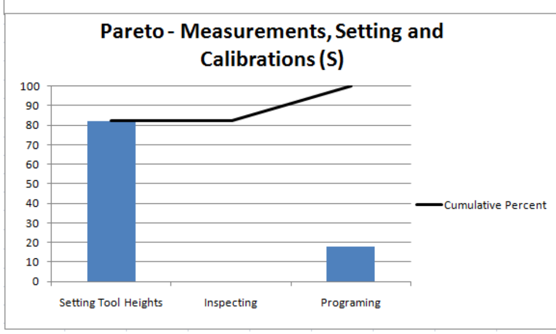
Pareto Diagram - Changeover (C_DE)
%
Time (h:mm:ss)
100
90
80
70
60
50
40
30
20
10
0
1:01:27
0:55:18
0:49:10
0:43:01
0:36:52
0:30:44
0:24:35
0:18:26
0:12:17
0:06:09
0:00:00
0:06:11
0:08:29
0:14:55
0:31:05
0:00:47
1:01:27
Preperation and Aftercare (P)
Mounting Tools and Fixtures (M)
Measurement, Settings, and Calibrations (S)
Trail Run (T)
Distraction (D)
Total
External
Internal
Cumulative Percent



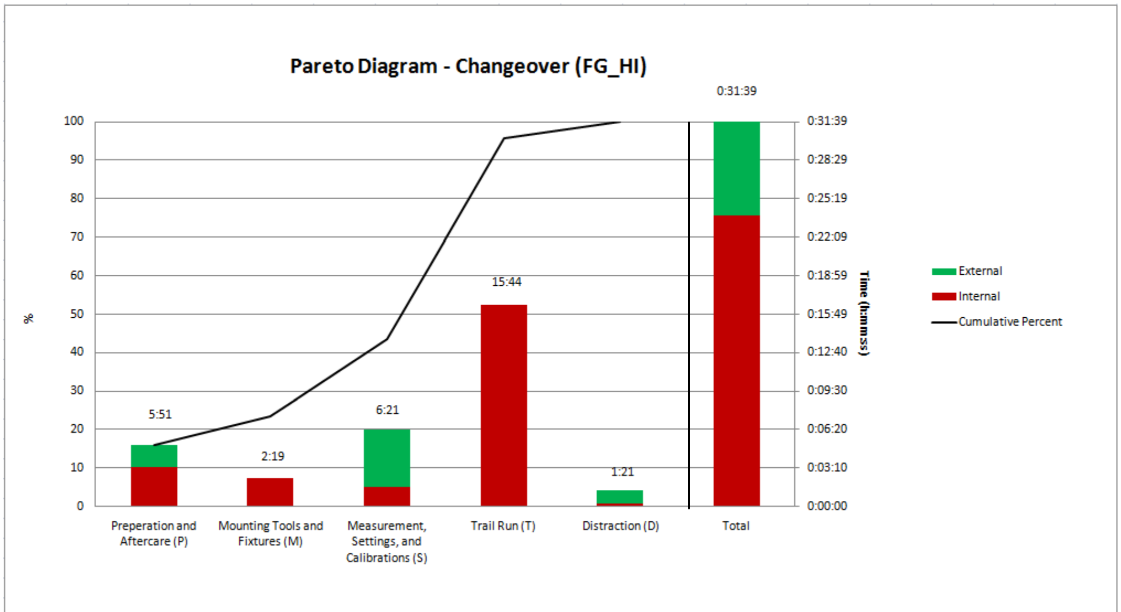
Pareto - Preperation and Aftercare (P)
%
100
90
80
70
60
50
40
30
20
10
0
Tool Setting
Paper Work
Cleaning, Organizing
Retrieving Boxes and Raw Materials
Cumulatative Percent



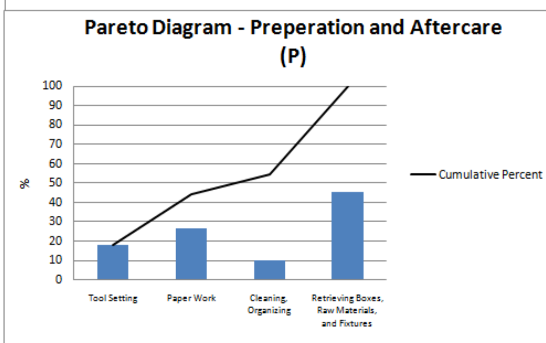
Pareto - Mounting Tools and Fixtures (M)
%
100
90
80
70
60
50
40
30
20
10
0
Removing and Attaching Fixtures
Cleaning
Removing and Attaching Tools
Cumulative Percent



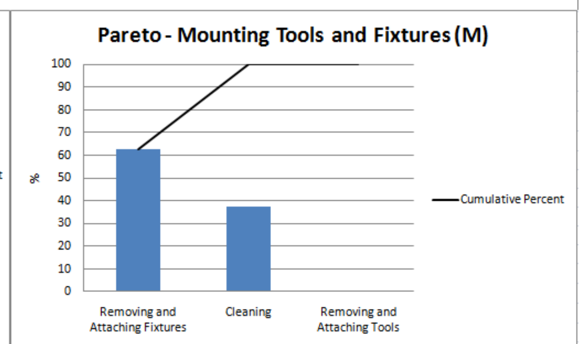
Pareto - Measurements, Setting and Calibrations (S)
100
90
80
70
60
50
40
30
20
10
0
Setting Tool Heights
Inspecting
Programing
Cumulative Percent



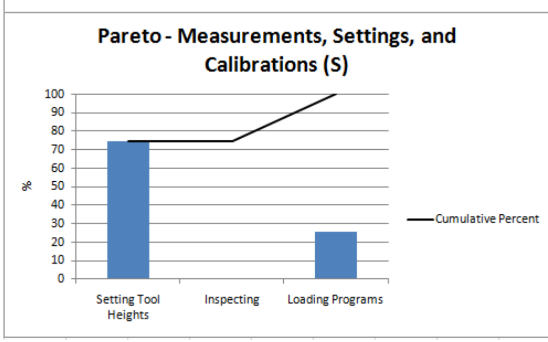
Pareto Diagram - Changeover (FG_HI)
0:31:39
%
Time (h:mm:ss)
5:51
2:19
6:21
15:44
1:21
Preperation and Aftercare (P)
Mounting Tools and Fixtures (M)
Measurement, Settings, and Calibrations (S)
Trail Run (T)
Distraction (D)
Total
External
Internal
Cumulative Percent



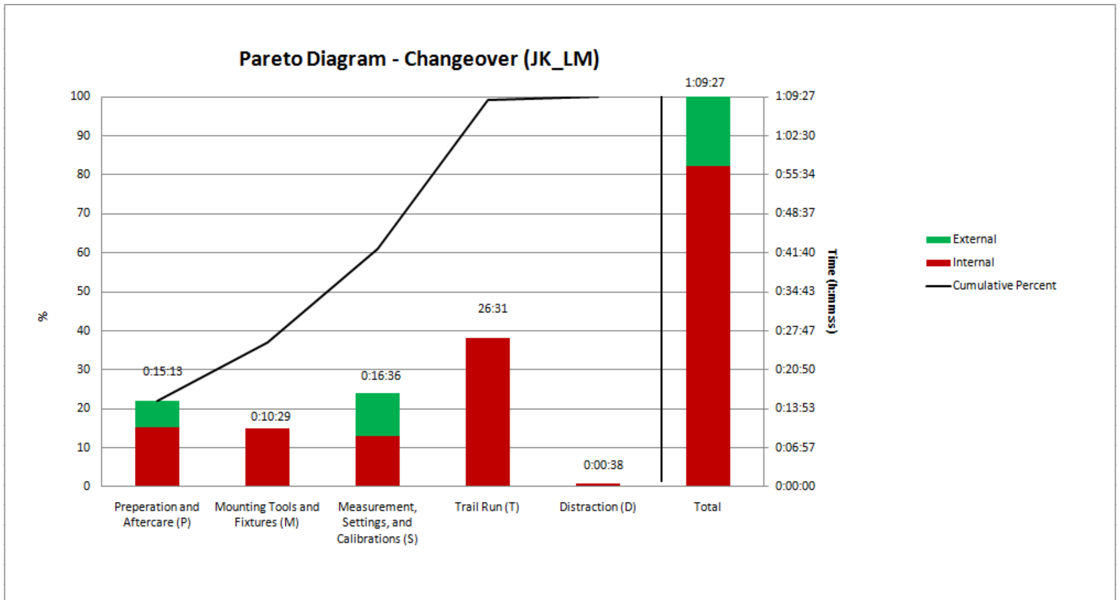
Pareto Diagram - Preperation and Aftercare (P)
%
Tool Setting
Paper Work
Cleaning, Organizing
Retrieving Boxes, Raw Materials, and Fixtures
Cumulative Percent

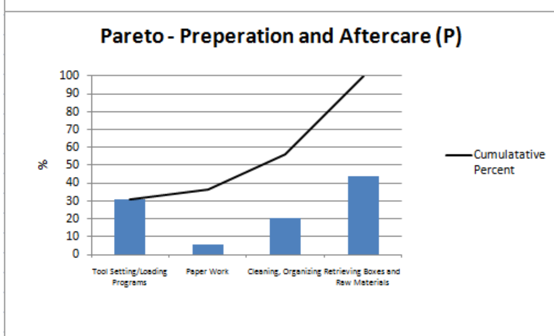


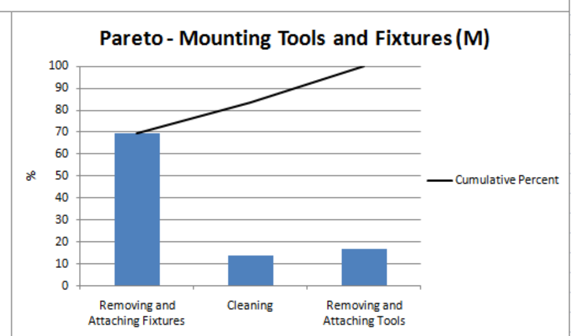
Pareto - Mounting Tools and Fixtures (M)
%
Removing and Attaching Fixtures
Cleaning
Removing and Attaching Tools
Cumulative Percent

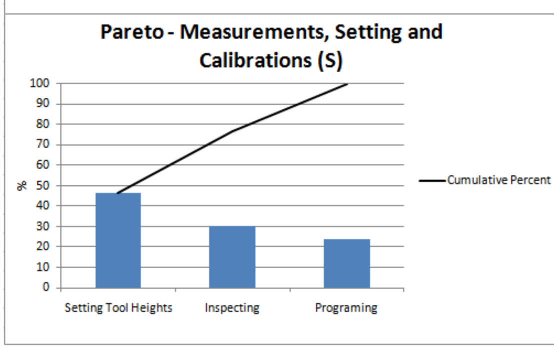


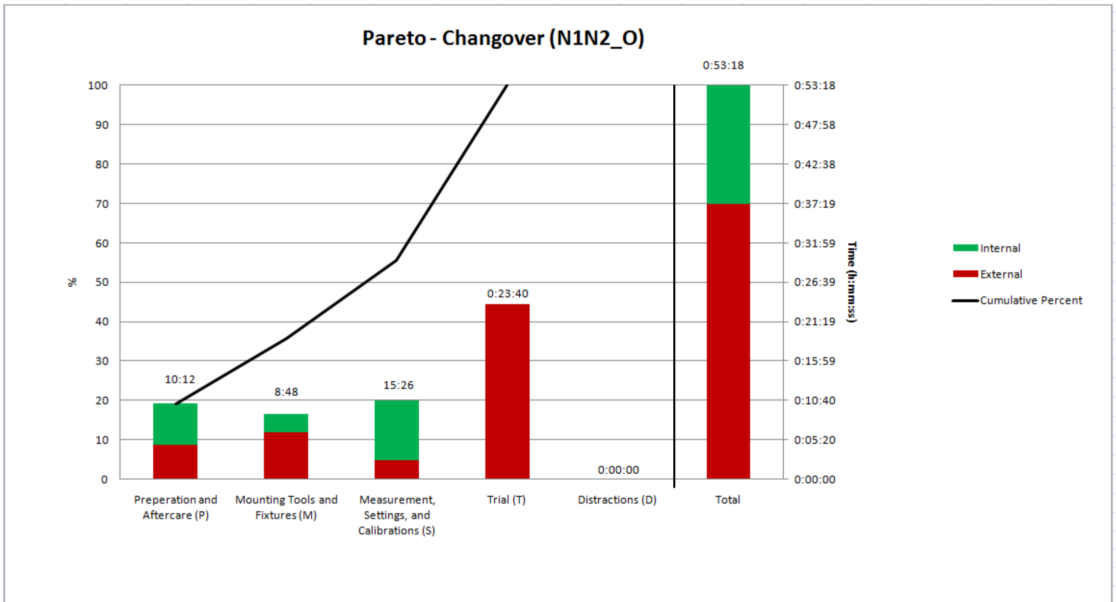
Pareto - Measurements, Settings, and Calibrations (S)
%
Setting Tool Heights
Inspecting
Loading Programs
Cumulative Percent

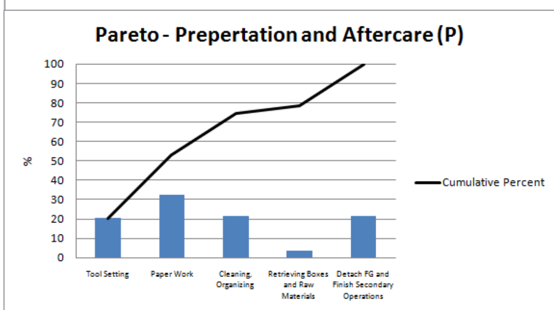

Pareto Diagram - Changeover (JK_LM)
%
Time (h:mm:ss)
0:15:13
0:10:29
0:16:36
26:31
0:00:38
1:09:27
Preperation and Aftercare (P)
Mounting Tools and Fixtures (M)
Measurement, Settings, and Calibrations (S)
Trail Run (T)
Distraction (D)
Total
External
Internal
Cumulative Percent

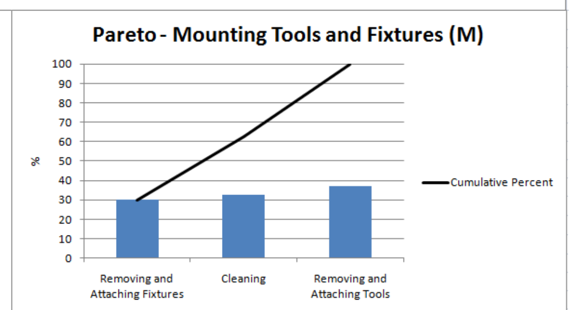

Pareto - Preperation and Aftercare (P)
%
Tool Setting/Loading Programs
Paper Work
Cleaning, Organizing
Retrieving Boxes and Raw Materials
Cumulatative Percent

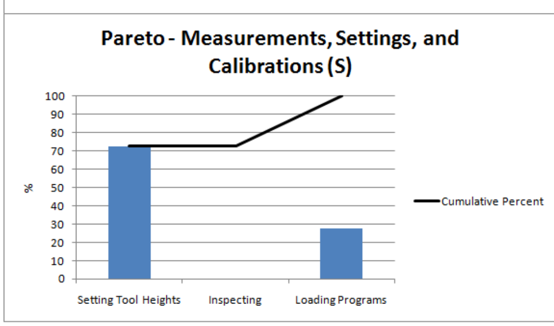

Pareto - Mounting Tools and Fixtures (M)
%
Removing and Attaching Fixtures
Cleaning
Removing and Attaching Tools
Cumulative Percent

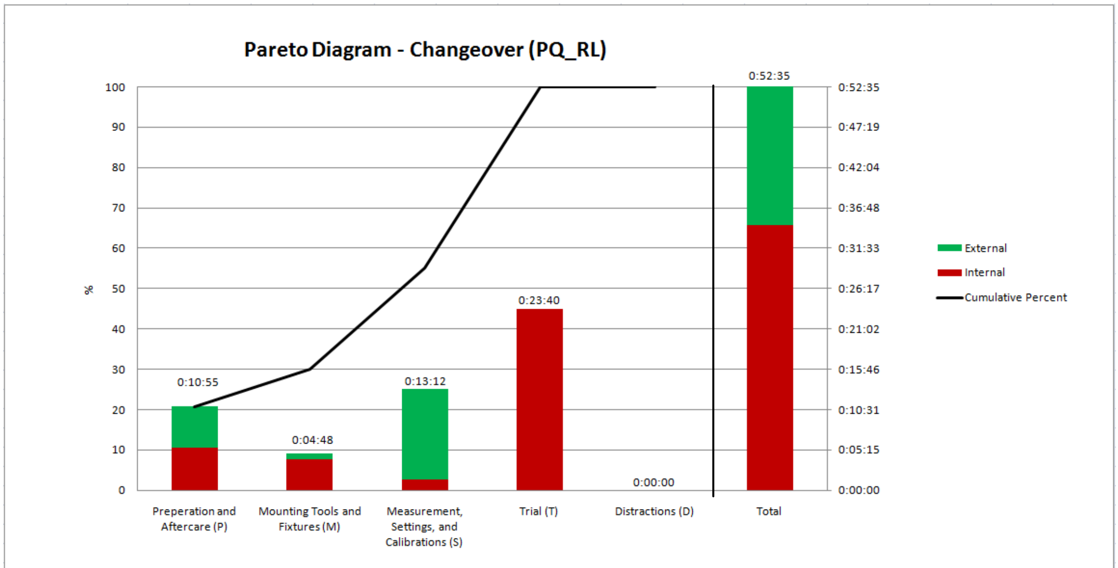

Pareto - Measurements, Setting and Calibrations (S)
%
Setting Tool Heights
Inspecting
Programing
Cumulative Percent

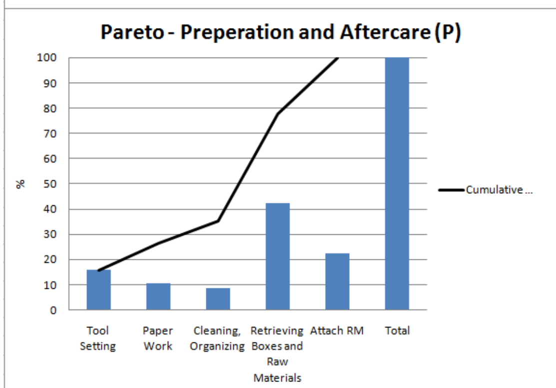

Pareto - Changover (N1N2_O)
100
90
80
70
60
50
40
30
20
10
0
%
0:53:18
0:47:58
0:42:38
0:37:19
0:31:59
0:26:39
0:21:19
0:15:59
0:10:40
0:05:20
0:00:00
Time (h:mm:ss)
10:12
8:48
15:26
0:23:40
0:00:00
0:53:18
Preperation and Aftercare (P)
Mounting Tools and Fixtures (M)
Measurement, Settings, and Calibrations (S)
Trial (T)
Distractions (D)
Total
Internal
External
Cumulative Percent

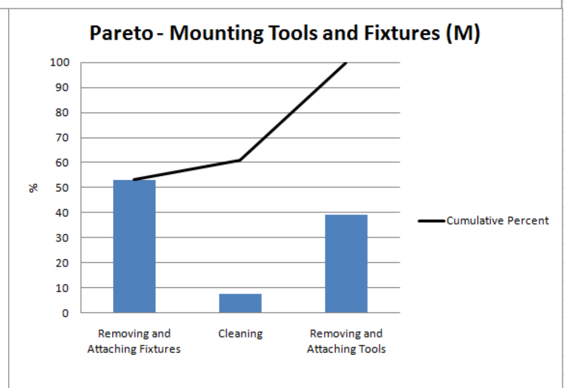

Pareto - Prepertation and Aftercare (P)
100
90
80
70
60
50
40
30
20
10
0
%
Tool Setting
Paper Work
Cleaning, Organizing
Retrieving Boxes and Raw Materials
Detach FG and Finish Secondary Operations
Cumulative Percent

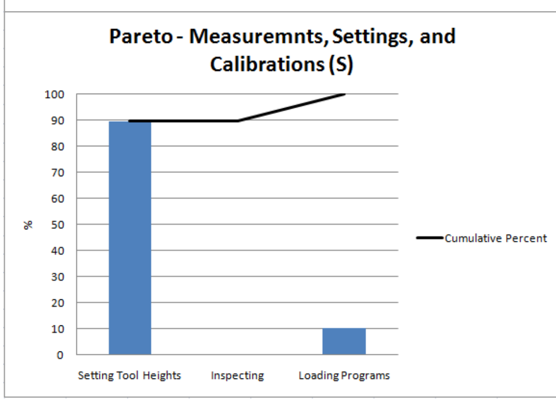

Pareto - Mounting Tools and Fixtures (M)
100
90
80
70
60
50
40
30
20
10
0
%
Removing and Attaching Fixtures
Cleaning
Removing and Attaching Tools
Cumulative Percent


Pareto - Measurements, Settings, and Calibrations (S)
100
90
80
70
60
50
40
30
20
10
0
%
Setting Tool Heights
Inspecting
Loading Programs
Cumulative Percent


Pareto Diagram - Changeover (PQ_RL)
%
0:10:55
0:04:48
0:13:12
0:23:40
0:00:00
0:52:35
Preperation and Aftercare (P)
Mounting Tools and Fixtures (M)
Measurement, Settings, and Calibrations (S)
Trial (T)
Distractions (D)
Total
External
Internal
Cumulative Percent


Pareto - Preperation and Aftercare (P)
%
Tool Setting
Paper Work
Cleaning, Organizing
Retrieving Boxes and Raw Materials
Attach RM
Total
Cumulative ...


Pareto - Mounting Tools and Fixtures (M)
%
Removing and Attaching Fixtures
Cleaning
Removing and Attaching Tools
Cumulative Percent


Pareto - Measuremnts, Settings, and Calibrations (S)
%
Setting Tool Heights
Inspecting
Loading Programs
Cumulative Percent

APPENDIX III - PAIRING DATA

Top Products that Represent 80% of the Company's Profit

Unit Rank	Unit Type	Part #/Rank	Fixture #	Cycle Time	Pieces/Cycle	Tools	Pieces/Unit	Units/Cycle	Cycle Time/ Piece	Overall Changeover Time		
										Unpaired	Paired	Difference
1	Product Line A											
		1	14	14	18	3	1	18	0.777777778	1:54:28	0:57:14	0:57:14
		2	92	5	4	6	1	4	1.25			
2	Product Line A											
		3	14	30		3	1	0		1:54:28	0:57:14	0:57:14
		4	91	4	4	5	1	4	1			
3	Product Line A											
		5	37	12	18	3	1	18	0.666666667	1:54:28	0:57:14	0:57:14
		6	166	3.5	4	7	1	4	0.875			
4	Product Line A											
		7	16	6.5	5	2	1	5	1.3	1:54:28	0:57:14	0:57:14
		8	98		2	5	1	2	0			
5	Product Line A											
		9	37	12	18	3	1	18	0.666666667	1:54:28	0:57:14	0:57:14
		10	63 + 64	23	28	9	1	28	0.821428571			
6	Product Line A											
		11	14	14	18	3	1	18	0.777777778	1:54:28	0:57:14	0:57:14
		12	47	6.5	4	7	1	4	1.625			
7	Product Line A											
		13	13	5	8	2	1	8	0.625	1:54:28	0:57:14	0:57:14
		14	99	6	3	6	1	3	2			
8	Product Line A											
		15	14	31		3	1	0		1:54:28	0:57:14	0:57:14
		16	162	4	4	5	1	4	1			
9	Product Line A											
		17	14	30		3	1	0		1:54:28	0:57:14	0:57:14
		18	46	7	5	7	1	5	1.4			
10	Product Line C											
		19	85	18.5	3	6	2	1.5	6.166666667	2:51:42	1:54:28	0:57:14
		20	66	5	4	6	1	4	1.25			
		21	71	2.5	4	3	1	4	0.625			
11	Product Line A											
		22	35	17	16	4	1	16	1.0625	1:54:28	0:57:14	0:57:14
		23	111	3.5	4	6	1	4	0.875			
12	Product Line C											
		24	Mod 3	4	6	3	1	6	0.666666667	1:54:28	0:57:14	0:57:14
		25	19	8.5	4	7	1	4	2.125			
13	Product Line A											
		26	35	17	16	4	1	16	1.0625	1:54:28	0:57:14	0:57:14
		27	65	2.5	4	7	1	4	0.625			
14	Product Line C											
		28	126	3	16	3	1	16	0.1875	0:57:14	0:57:14	0:00:00
15	Product Line A											
		29	37	12	18	3	1	18	0.666666667			
		30	168	35	4	8	1	4	8.75	1:54:28	0:57:14	0:57:14
16	Product Line B											
		31	75	8.5	4	4	1	4	2.125			
		32	56	31.5	10	6	1	10	3.15	1:54:28	0:57:14	0:57:14
17	Product Line C											
		33	165		3	4	2	1.5	0	3:48:56	1:54:28	1:54:28
		34	86	18	24	4	4	6	0.75			
		35	30	13.5	12	4	1	12	1.125			
		35	42	6.5	12	4	1	12	0.541666667			
18	Product Line A											
		36	13	11.5	8	5	1	8	1.4375	1:54:28	0:57:14	0:57:14
		37	103		2	7	1	2	0			

19 Product Line A											
	38	65	4.5	4	6	1	4	1.125	0:57:14	0:57:14	0:00:00
20 Product Line C											
	39	164		4	3	1	4	0	1:54:28	0:57:14	0:57:14
	40	Mod 1		6	4	2	3	0			
21 Product Line C											
	41	126	3	16	3	1	16	0.1875	1:54:28	0:57:14	0:57:14
	42	Mod 5	6.16	6	4	1	6	1.026666667			
22 Product Line A											
	43	119	5.5	4	7	1	4	1.375	1:54:28	0:57:14	0:57:14
23 Product Line A											
	44	16	6.5	5	2	1	5	1.3			
	45	48	12	4	11	1	4	3	1:54:28	0:57:14	0:57:14
24 Product Line A											
	46	14	14	18	3	1	18	0.777777778			
	47	159	11	2	10	1	2	5.5	1:54:28	0:57:14	0:57:14
25 Product Line C											
	48	108	5	4	6	2	2	1.25	3:48:56	1:54:28	1:54:28
	49	28	11.5	8	6	1	8	1.4375			
	50	1	7.5	24	3	2	12	0.3125			
	51	1	12	24	3	2	12	0.5			
26 Product Line A											
	52	36	8.5	18	3	1	18	0.472222222	1:54:28	0:57:14	0:57:14
	53	52	3	4	7	1	4	0.75			
27 Product Line A											
	54	111	3.5	4	6	1	4	0.875	0:57:14	0:57:14	0:00:00
28 Product Line B											
	55	73	14	10	1	1	10	1.4	0:57:14	0:57:14	0:00:00
29 Product Line A											
	56	13	11.5	8	5	1	8	1.4375	0:57:14	0:57:14	0:00:00
30 Product Line A											
	57	14	31		3	1	0		1:54:28	0:57:14	0:57:14
	58	160		5	7	1	5	0			
31 Product Line A											
	59	35	17	16	4	1	16	1.0625	1:54:28	0:57:14	0:57:14
	60	44	4	5	8	1	5	0.8			
32 Product Line C											
	61	164	7	4	3	1	4	1.75	4:46:10	2:51:42	1:54:28
	62	MOD 1	31.5	6	4	1	6	5.25			
	63	Mod 3		6	4	1	6	0			
	64	155	11	15	4	1	15	0.733333333			
	65	Mod 3	3	6	4	1	6	0.5			
33 Product Line C											
	66	126	3	16	3	2	8	0.1875	0:57:14	0:57:14	0:00:00
34 Product Line A											
	67	166	3.5	4	5	1	4	0.875			
35 Product Line C											
	68	84	12	18	4	2	9	0.666666667	4:46:10	2:51:42	1:54:28
	69	84	12	18	4	2	9	0.666666667			
	70	45	2	6	3	4	1.5	0.333333333			
	71	53	2	2	1	2	1	1			
	71	122	10.5	2	12	2	1	5.25			
36 Product Line C											
	72	7	7	20	4	2	10	0.35	3:48:56	1:54:28	1:54:28
	73	5	8.5	12	4	2	6	0.708333333			
	74	50	6.5	4	4	2	2	1.625			
	75	29	9	10	6	1	10	0.9			

37 Product Line C												
		76	117	3.5	1	8	1	1	3.5	2:51:42	1:54:28	0:57:14
		77	117			4	1	0				
		78	MOD 5	6.16	6	4	1	6	1.026666667			
38 Product Line A	*Not Milling Needed											
39 Product Line C												
		79	126	3	16	3	2	8	0.1875	0:57:14	0:57:14	0:00:00
40 Product Line A												
		80	118	4.5	4	5	1	4	1.125	0:57:14	0:57:14	0:00:00
41 Product Line A												
		81	11	6	13.5	6	1	13.5	0.444444444	1:54:28	0:57:14	0:57:14
		82	130		2	10	1	2	0			
42 Product Line C												
		83	165		3	4	2	1.5	0	3:48:56	1:54:28	1:54:28
		84	86	24	30	4	4	7.5	0.8			
		85	30	13.5	12	3	1	12	1.125			
		85	42	6.5	12	4	1	12	0.541666667			
43 Product Line C												
		86	7	7	20	4	2	10	0.35	3:48:56	1:54:28	1:54:28
		87	5	8.5	12	4	2	6	0.708333333			
		88	50	6.5	4	4	2	2	1.625			
		89	29	9	10	6	1	10	0.9			
44 Product Line A												
		90	34	7.5	3	8	1	3	2.5	0:57:14	0:57:14	0:00:00
45 Product Line C												
		91	7	3	20	2	2	10	0.15	4:46:10	2:51:42	1:54:28
		92	152	3.5	10	2	2	5	0.35			
		93	4	10.5	12	4	2	6	0.875			
		94	163	5	3	4	2	1.5	1.666666667			
		95	40	4	6	2	1	6	0.666666667			
46 Product Line B												
		96	150		4	4	1	4	0	0:57:14	0:57:14	0:00:00
47 Product Line A												
		97	36	13.5	18	3	1	18	0.75	1:54:28	0:57:14	0:57:14
		98	52	3	4	7	1	4	0.75			
48 Product Line B												
		99	72	17.5	12	4	1	12	1.458333333	1:54:28	0:57:14	0:57:14
		100	54	6.5	10	4	1	10	0.65			
49 Product Line C												
		101	7	3	20	2	2	10	0.15	4:46:10	2:51:42	1:54:28
		102	152	3.5	10	2	2	5	0.35			
		103	4	10.5	12	4	2	6	0.875			
		104	163	5	3	4	2	1.5	1.666666667			
		105	29	9	10	6	1	10	0.9			
50 Product Line B												
		106	156	19.5	8	4	1	8	2.4375	3:48:56	1:54:28	1:54:28
		107	153		4	2	1	4	0			
		108	132		4	6	1	4	0			
		109	153	19	4	8	1	4	4.75			
51 Product Line C												
		110	MOD 5	6.16	6	4	2	3	1.026666667	0:57:14	0:57:14	0:00:00
52 Product Line B												
		111	74	23.5	8	4	1	8	2.9375	0:57:14	0:57:14	0:00:00
53 Product Line C												
		112	126	3	16	3	1	16	0.1875	1:54:28	0:57:14	0:57:14
		113	MOD 5	6.16	6	4	1	6	1.026666667			

54 Product Line A											
	114	49	22.5	8	12	1	8	2.8125	1:54:28	0:57:14	0:57:14
	115	13	5	8	2	1	8	0.625			
55 Product Line A											
	116	22	1	5	1	2	2.5	0.2	2:51:42	1:54:28	0:57:14
	117	100	1	2	2	1	2	0.5			
	118	11	6	13.5	6	2	6.75	0.444444444			
56 Product Line C											
	119	126	3	16	3	1	16	0.1875	0:57:14	0:57:14	0:00:00
57 Product Line B											
	120	75	31.5	10	4	1	10	3.15	3:48:56	1:54:28	1:54:28
	121	153	19	4	8	1	4	4.75			
	122	153		4	2	1	4	0			
	123	89	7.5	4	6	1	4	1.875			
58 Product Line C											
	124	MOD 5	6.16	6	4	2	3	1.026666667	0:57:14	0:57:14	0:00:00
59 Product Line C											
	125	108	5	4	6	2	2	1.25	2:51:42	1:54:28	0:57:14
	126	MOD 4	3.5	8	3	2	4	0.4375			
	127	28	11.5	8	6	1	8	1.4375			
60 Product Line C											
	128	117	3.5	1	8	1	1	3.5	2:51:42	1:54:28	0:57:14
	129	117		1	4	1	1	0			
	130	MOD 5	6.16	6	4	1	6	1.026666667			
61 Product Line C											
	131	117	3.5	1	8	1	1	3.5	2:51:42	1:54:28	0:57:14
	132	117		1	4	1	1	0			
	133	126	3	16	3	1	16	0.1875			
62 Product Line A											
	134	168	4	4	6	1	4	1	0:57:14	0:57:14	0:00:00
63 Product Line A											
	135	126	3	16	3	2	8	0.1875	0:57:14	0:57:14	0:00:00
64 Product Line A											
	136	63	33.5	28	9	1	28	1.196428571	0:57:14	0:57:14	0:00:00
65 Product Line B											
	137	73		10	4	1	10	0	0:57:14	0:57:14	0:00:00
66 Product Line C											
	138	108	4	5	6	2	2.5	0.8	2:51:42	1:54:28	0:57:14
	139	Mod 4	3.5	8	6	2	4	0.4375			
	140	28	11.5	8	6	1	8	1.4375			
67 Product Line C											
	141	MOD 1		6	4	1	6	0	2:51:42	1:54:28	0:57:14
	142	163	5	3	4	1	3	1.666666667			
	143	152	10	10	6	1	10	1			
68 Product Line A											
	144	52	5.5	4	6	1	4	1.375	0:57:14	0:57:14	0:00:00
69 Product Line C											
	145	7	3	20	2	2	10	0.15	4:46:10	2:51:42	1:54:28
	146	6	11.5	12	4	2	6	0.958333333			
	147	4	10.5	12	4	2	6	0.875			
	148	163	5	3	4	2	1.5	1.666666667			
	149	29	9	10	6	1	10	0.9			
70 Product Line A											
	150	93	9	6	5	1	6	1.5	0:57:14	0:57:14	0:00:00
71 Product Line C											
	151	MOD 5	6.16	6	4	1	6	1.026666667	0:57:14	0:57:14	0:00:00

72 Product Line B											
	152	73	14	10	4	1	10	1.4	3:48:56	1:54:28	1:54:28
	153	78	6	4	5	1	4	1.5			
	154	79	1.5	8	1	1	8	0.1875			
	155	90	8.5	8	6	1	8	1.0625			
73 Product Line B											
	156	72	17.5	12	4	1	12	1.458333333	3:48:56	1:54:28	1:54:28
	157	153	4.5	8	4	1	8	0.5625			
	158	157		8	3	1	8	0			
	159	157	8.5	8	4	1	8	1.0625			
74 Product Line A											
	160	52	5.5	4	7	1	4	1.375	0:57:14	0:57:14	0:00:00
							Averages:		2:09:34	1:18:42	0:50:52

Average Changeover Time	0:57:14

Units	74
Units to Chiron	73
Part #'s	160
Total Operations	159
Missing cycle times	20

Product Line A	34
Product Line C	30
Product Line B	10
Product Line A Parts #'s	58
Product Line C Part #'s	78
Product Line B Part #'s	24

Highlighted Cells: Data not Available

Parts	Unpaired	Paired
1	0:57:14	0:57:14
2	1:54:28	0:57:14
3	2:51:42	1:54:28
4	3:48:56	1:54:28
5	4:46:10	2:51:42

APPENDIX IV - MACRO OUTPUT

Tools - Product Line A - Unpaired

Binary Value		Part #s \ Tools	Decimal Euivelent	Rank	Oredered?	Random Numbers	Number of Tools for 2 Tables	Removed Attached		Total Tools (used for changeover)
		Previous Job								
5.49756E+11	39	Part #9	1.29127E+20	1	TRUE	0.081001869	5	8	Removed	13
2.74878E+11	38	Part #12	8.7622E+19	2	TRUE	0.220972487		4	Attached	15
1.37439E+11	37	Part #21	7.78222E+19	3	TRUE	0.918167899	12	3		0
68719476736	36	Part #13	9.79533E+18	4	TRUE	0.272389787		10		15
34359738368	35	Part #4	9.79083E+18	5	TRUE	0.37955474	10	5		0
17179869184	34	Part #8	9.73172E+18	6	TRUE	0.759781722		3		15
8589934592	33	Part #19	9.51435E+18	7	TRUE	0.32367881	9	6		0
4294967296	32	Part #29	2.34191E+18	8	TRUE	0.838209475		5		12
2147483648	31	Part #17	2.30587E+18	9	TRUE	0.990527151	4	8		0
1073741824	30	Part #11	2.30586E+18	10	TRUE	0.127943608		3		15
536870912	29	Part #3	3.07655E+17	11	TRUE	0.32893914	11	4		0
268435456	28	Part #26	2.90204E+17	12	TRUE	0.110398759		11		17
134217728	27	Part #22	1.81974E+17	13	TRUE	0.025130036	10	7		0
67108864	26	Part #23	1.47072E+17	14	TRUE	0.568999911		6		17
33554432	25	Part #10	2.0267E+16	15	TRUE	0.447596813	10	7		0
16777216	24	Part #15	1.80856E+16	16	TRUE	0.113939762		7		18
8388608	23	Part #2	1.80849E+16	17	TRUE	0.064910329	15	3		0
4194304	22	Part #18	1.80152E+16	18	TRUE	0.729953826		8		26
2097152	21	Part #6	1.80144E+16	19	TRUE	0.120758162	16	10		0
1048576	20	Part #7	2.32299E+15	20	TRUE	0.426401599		11		23
524288	19	Part #27	2.25235E+15	21	TRUE	0.511888771	11	12		0
262144	18	Part #24	8.37519E+11	22	TRUE	0.817757989		7		15
131072	17	Part #14	8.36982E+11	23	TRUE	0.362885765	9	6		0
65536	16	Part #25	5.51369E+11	24	TRUE	0.694682507		4		16
32768	15	Part #1	5.50025E+11	25	TRUE	0.923809574	11	5		0
16384	14	Part #28	1612713992	26	TRUE	0.395071827		7		14
8192	13	Part #5	671088647	27	TRUE	0.118322818	5	10		0
4096	12	Part #16	134217732	28	TRUE	0.289450961		4		4
2048	11	Part #20	3	29	TRUE	0.272920262	2	3		0
1024	10		0	30	TRUE			0		0
512	9		0	30	TRUE		0	0		0
256	8		0	30	TRUE			0		0
128	7		0	30	TRUE		0	0		0
64	6		0	30	TRUE			0		0
32	5		0	30	TRUE		0	0		0
16	4		0	30	TRUE			0		0
8	3		0	30	TRUE		0	0		0
4	2		0	30	TRUE			0		0
2	1		0	30	TRUE		0	0		0
1	0		0	30	FALSE			0		0

Total Tool Changeover Time	0:23:23
Tool Changeover Time	00:07.5
Tool Changeovers	13
Changeovers	15

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	15	14	14	15	15	15	15	15	14	14	13	13	14.333	13	15
Initial Changeover Time	0:34:00	0:27:45	0:29:07	0:28:53	0:31:15	0:32:22	0:30:37	0:30:30	0:32:00	0:28:53	0:30:37	0:33:08	30:45.6	27:45.0	34:00.0
Tool Changeovers	13	12	12	12	12	12	11	13	9	13	13	13	12.083	9	13
Changeover Time	0:27:07	0:25:53	0:23:52	0:26:22	0:24:52	0:26:08	0:23:23	0:23:08	0:25:37	0:23:23	0:25:07	0:23:23	24:51.3	23:08.0	27:07.5
Tool Changeoever Savings	2	2	2	3	3	3	4	2	5	1	0	0	2.25	0	5
Changeover Time Savings	0:06:53	0:01:52	0:05:15	0:02:30	0:06:22	0:06:15	0:07:15	0:07:22	0:06:23	0:05:30	0:05:30	0:09:45	05:54.3	01:52.5	09:45.0

Minumum
0:23:08

Tools - Product Line A - Paired

Binary Value: # 8 4 2 1
9 8 7 6 5 4 3 2 1 0

Part #s/Tools: 7, 1· 1' 1, 3, 2· 1, 9, 2' 3, 1' 1' 1! 5, 1, 3, 1, #: 5, #: 9, 5, 4! 2' 3, 1! 1! #: 3, 3, 5, 1, 2 9, #: 3, 1, 3, 5, 1 3, 3, 3, 1! #: 1, 6. 5· 1· 3, 2 # 9, 1! 3, 3, 1, 1 #: 1, 1 1' 3, 7, 6· 1, 7/8 4

Previous Job: 1 1 1 1 1 1 1 1 1

Binary Value		Product(s)	Part #s/Tools	Tool marks	Decimal Equivelent	Rank	Ordered	Random Number	Tools	Remove	Attache	Total Tools (used in changeover)
524288	#	Product #16	Part #31/Part #32	1 1 1 1 1 1 1 1	1.46997E+20	1	TRUE	0.32860838	8	9	7	17
262144	#	Product #12	Part #23/Part #24	1 1 1 1 1 1 1 1 1 1 1 1	1.38925E+20	2	TRUE	0.67710055	12	4	8	16
131072	#	Product #1	Part #1/Part #2	1 1 1 1 1 1 1 1 1 1	1.176E+20	3	TRUE	0.421490997	10	10	8	20
65536	#	Product #9	Part #17/Part #18	1 1 1 1 1 1 1 1 1 1 1	1.15294E+20	4	TRUE	0.748828566	10	4	4	14
32768	#	Product #14	Part #27/Part #28	1 1 1 1 1 1 1 1 1 1	1.15294E+20	5	TRUE	0.954797652	10	2	2	12
16384	#	Product #8	Part #15/Part #16	1 1 1 1 1 1 1 1	7.60947E+19	6	TRUE	0.3828543	8	5	3	13
8192	#	Product #17	Part #33/Part #34	1 1 1 1 1 1 1 1	7.40769E+19	7	TRUE	0.349020499	8	4	4	12
4096	#	Product #2	Part #3/Part #4	1 1 1 1 1 1 1 1 1 1 1 1 1	7.40755E+19	8	TRUE	0.788947788	13	5	10	18
2048	#	Product #20	Part #39/Part #40	1 1 1 1 1 1 1 1 1	7.37889E+19	9	TRUE	0.270100662	9	10	6	19
1024	#	Product #19	Part #37/Part #38	1 1 1 1 1 1 1 1 1 1 1	7.37882E+19	10	TRUE	0.874005403	11	6	8	17
512	9	Product #4	Part #7/Part #8	1 1 1 1 1 1 1 1 1 1	7.37881E+19	11	TRUE	0.685877581	10	5	4	15
256	8	Product #11	Part #21/Part #22	1 1 1 1 1 1 1 1 1 1 1 1	7.37881E+19	12	TRUE	0.454600416	12	6	8	18
128	7	Product #6	Part #11/Part #12	1 1 1 1 1 1 1 1 1 1 1	6.47798E+19	13	TRUE	0.96923248	11	10	9	21
64	6	Product #5	Part #9/Part #10	1 1 1 1 1 1 1	4.31625E+19	14	TRUE	0.163701748	7	8	4	15
32	5	Product #10	Part #19/Part #20	1 1 1 1 1 1 1 1 1 1 1	4.82787E+18	15	TRUE	0.973520501	11	4	8	15
16	4	Product #15	Part #29/Part #30	1 1 1 1 1 1 1 1 1 1 1	1.80821E+17	16	TRUE	0.765701081	11	9	9	20
8	3	Product #18	Part #35/Part #36	1 1 1 1 1 1 1 1 1 1 1 1	6.42149E+14	17	TRUE	0.809550105	12	8	9	20
4	2	Product #13	Part #25/Part #26	1 1 1 1 1 1 1 1 1 1 1	6.42149E+14	18	TRUE	0.748434483	11	1	0	12
2	1	Product #7	Part #13/Part #14	1 1 1 1 1 1 1 1 1 1	5.67537E+14	19	TRUE	0.610380957	10	5	4	15
1	0	Product #3	Part #5/Part #6	1 1 1 1 1 1 1 1 1	2.4098E+11	20	FALSE	0.453241414	0	6	5	15

Decimal Equivelent: # 8
Rank: 1 2 3 3 5 6 7 8 9 #
Ordered?: #
Ordered?: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
Random Numbers: 0 1 1 1 0 0 0 1 1 0 1 1 0 1 1 1 0 0 0 0 1 0 0 0 1 1 1 1 1 1 1 1 0 1 1 0 0 0 1 0 0 1 0 1 1 1 1 0 1 0 1 0 0 1 1 0 0 1 0 0 0 0 0 0 0 1 0 1

Tool Changeovers	17
Tool Changeover Time	00:07.5
Total Tool Changeover Time	0:30:07

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	19	20	20	19	19	19	19	16	19	18	20	20	19	16	20
Initial Total Tool Changeover Time	0:38:00	0:39:00	0:39:37	0:36:30	0:40:37	0:41:22	0:39:07	0:37:37	0:38:30	0:38:07	0:38:53	0:40:00	0:38:57	0:36:30	0:41:22
Tool Changeovers	17	18	16	17	17	16	18	17	16	18	16	17	16.917	16	18
Total Tool Changeover Time	0:30:52	0:31:37	0:32:07	0:31:00	0:30:37	0:33:15	0:32:45	0:34:45	0:28:53	0:31:22	0:30:52	0:30:07	0:31:31	0:28:53	0:34:45
Tool changover delta	2	2	4	2	2	3	1	-1	3	0	4	3	2.0833	-1	4
Tool Changeover Time Savings	0:07:07	0:07:23	0:07:30	0:05:30	0:10:00	0:08:08	0:06:22	0:02:53	0:09:37	0:06:45	0:08:00	0:09:52	0:07:26	0:02:53	0:10:00

Minimum
0:28:53

Tools - Product Line B - Unpaired

Decimal Equivalent	Part #s\Tools / Previous Jobs		Tools (1 = used)	Decimal Euivelent	Rank	Ordered?	Random Numbers	Number of Tools For 2 Tables	Removed / Attached	Total Tools (used for changeover)
	Decimal Equivalent		# 8 4 2 1							
			# 9 8 7 6 5 4 3 2 1 0							
			7, 9, 1· 1, 1# 3, 1· 1, 2' 4' 1' 1, 1, 5. 4' 5, 3, 1' 5. 9, 4' 1' 9, .5 1' 3, #' 2' 1, 1' 1, 1' 1, 1. 1' 1, # 2· 3, 1, 3, 8. 1· 1· 1, 5, 3, 5' 1, 8· 3. 1, 3. #' 9, 5, 5. 5. 7. 5, 1 1, 3, 3, 1' 16.75							
			1 1 1 1 1 1							
5.49756E+11	39	Part #5	1 1 1 1 1 1 1 1	1.46997E+20	1	TRUE	0.20882291	9	6 Removed	15
2.74878E+11	38	Part #11	1 1 1 1	1.29415E+20	2	TRUE	0.314819124		7 Attached	20
1.37439E+11	37	Part #6	1 1 1 1 1 1 1	7.40707E+19	3	TRUE	0.061093453	12	8	0
68719476736	36	Part #18	1 1 1 1 1 1	7.37913E+19	4	TRUE	0.88541493		11	16
34359738368	35	Part #22	1 1 1	9.22348E+18	5	TRUE	0.715661004	4	12	0
17179869184	34	Part #10	1 1 1	9.22346E+18	6	TRUE	0.421604805		4	6
8589934592	33	Part #24	1 1 1	9.22346E+18	6	TRUE	0.419640124	5	1	0
4294967296	32	Part #25	1 1 1 1	9.22346E+18	8	TRUE	0.300270272		2	19
2147483648	31	Part #27	1 1 1 1 1 1 1 1 1 1 1 1 1	4.75975E+18	9	TRUE	0.988935601	14	5	0
1073741824	30	Part #3	1 1 1 1	1.46648E+17	10	TRUE	0.101576535		14	18
536870912	29	Part #28	1 1 1	7.3465E+16	11	TRUE	0.629956421	7	11	0
268435456	28	Part #20	1 1 1 1 1 1	7.24116E+16	12	TRUE	0.666748252		4	12
134217728	27	Part #30	1 1 1 1 1 1	7.23402E+16	13	TRUE	0.213485736	7	5	0
67108864	26	Part #12	1 1 1	7.23391E+16	14	TRUE	0.955480828		5	10
33554432	25	Part #19	1 1 1	7.23391E+16	14	TRUE	0.869889591	6	4	0
16777216	24	Part #2	1 1 1 1	3.82806E+16	16	TRUE	0.69464992		3	14
8388608	23	Part #23	1 1 1 1	2.56846E+15	17	TRUE	0.658306297	10	4	0
4194304	22	Part #1	1 1 1 1 1 1	5.6295E+14	18	TRUE	0.790192744		8	16
2097152	21	Part #4	1 1 1 1	1.40737E+14	19	TRUE	0.471399962	8	8	0
1048576	20	Part #14	1 1 1 1	3.51845E+13	20	TRUE	0.102880276		6	10
524288	19	Part #7	1 1 1	1.75922E+13	21	TRUE	0.111872924	5	5	0
262144	18	Part #17	1 1 1 1	8.79623E+12	22	TRUE	0.696842848		2	14
131072	17	Part #16	1 1 1 1 1 1	1.10327E+12	23	TRUE	0.616445608	9	5	0
65536	16	Part #15	1 1 1 1 1 1	1.10166E+12	24	TRUE	0.933225925		9	14
32768	15	Part #8	1 1 1 1	2100736	25	TRUE	0.46787157	5	9	0
16384	14	Part #29	1 1 1 1	2100480	26	TRUE	0.445431443		5	8
8192	13	Part #26	1 1 1 1	2272	27	TRUE	0.993575387	4	4	0
4096	12	Part #21	1 1 1 1	2272	27	TRUE	0.182849025		3	9
2048	11	Part #9	1 1 1	280	29	TRUE	0.869206253	6	4	0
1024	10	Part #13	1 1 1	7	30	TRUE	0.661062473		6	0
512	9			0	31	TRUE		0	0	0
256	8			0	31	TRUE			0	0
128	7			0	31	TRUE		0	0	0
64	6			0	31	TRUE			0	0
32	5			0	31	TRUE		0	0	0
16	4			0	31	TRUE			0	0
8	3			0	31	TRUE		0	0	0
4	2			0	31	TRUE			0	0
2	1			0	31	TRUE		0	0	0
1	0			0	31	FALSE			0	0

Decimal Equivelent	# #
Rank	1 2 2 4 5 6 6 6 9 #
Ordered?	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
Radom Numbers	0 0 1 1 1 1 1 0 1 1 1 0 0 1 0 1 0 1 1 1 1 1 1 0 0 0 1 1 0 1 0 0 0 0 0 0 0 0 0 1 0 1 1 1 1 1 1 0 1 1 0 1 0 0 0 1 1 0 1 0 0 1 0 1 0 0 0 1

Total Tool Changeover Time	0:22:30
Tool Changeover Time	00:07.5
Tool Changeovers	9
Changeovers	15

Run 1

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	14	13	15	13	15	13	14	13	11	14	13	14	13.5	11	15
Initial Changeover Time	0:29:30	0:29:37	0:28:22	0:29:45	0:28:53	0:28:45	0:29:15	0:28:00	0:28:22	0:29:30	0:30:07	0:29:15	29:06.9	28:00.0	30:07.5
Tool Changeovers	9	8	7	9	7	10	7	8	8	8	9	9	8.25	7	10
Changeover Time	0:22:15	0:22:00	0:22:45	0:22:30	0:22:30	0:23:52	0:23:00	0:22:15	0:21:15	0:22:00	0:22:45	0:22:30	22:28.1	21:15.0	23:52.5
Tool Changeover Savings	5	5	8	4	8	3	7	5	3	6	4	5	5.25	3	8
Changeover Time Savings	0:07:15	0:07:37	0:05:37	0:07:15	0:06:23	0:04:53	0:06:15	0:05:45	0:07:07	0:07:30	0:07:23	0:06:45	06:38.7	04:52.5	07:37.5

Minumum
0:21:15

Tools - Product Line B - Paired

Binary Value		Product(s)	Part #s/Tools	Tool columns (Binary Value # … 8 4 2 1 / # … 9 8 7 6 5 4 3 2 1 0)	#7 Parabolic Drill	Decimal Equivelent	Rank	Ordered?	Random Number	Tools	Removed	Attached	Total Tools
			Previous Jobs	1 1 1 1 1 1 1 1									
524288	#	Product #8	Part #22/Part #23	1 1 1 1 1 1 1 1 1 1		1.4743E+20	1	TRUE	0.921422078	10	2	2	12
262144	#	Product #6	Part #15/Part #16/Part #17/Part #18	1 1 1 1 1 1 1 1 1 1		1.46565E+20	2	TRUE	0.797460196	11	7	8	18
131072	#	Product #9	Part #24/Part #25	1 1 1 1 1 1 1 1 1 1 1		1.29271E+20	3	TRUE	0.83198244	16	6	11	22
65536	#	Product #10	Part #26/Part #27	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1		1.10807E+20	4	TRUE	0.724192784	13	12	9	25
32768	#	Product #13	Part #36/Part #37/Part #38/Part #39	1 1 1 1 1 1 1 1 1 1 1 1 1		1.01458E+20	5	TRUE	0.50390218	16	11	14	27
16384	#	Product #12	Part #32/Part #33/Part #34/Part #35	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1		9.69175E+19	6	TRUE	0.006677749	15	1	0	16
8192	#	Product #3	Part #5/Part #6	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1		9.68455E+19	7	TRUE	0.238597913	12	11	8	23
4096	#	Product #2	Part #3/Part #4	1 1 1 1 1 1 1 1 1 1 1 1		8.53162E+19	8	TRUE	0.703416247	8	12	8	20
2048	#	Product #7	Part #19/Part #20/Part #21	1 1 1 1 1 1 1 1		5.71417E+19	9	TRUE	0.618980769	8	6	6	14
1024	#	Product #1	Par#1/Part#2	1 1 1 1 1 1 1 1		2.88235E+19	10	TRUE	0.524638121	16	2	10	18
512	9	Product #4	Part #7/Part #8/Part #9/Part #10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1		2.88234E+19	11	TRUE	0.785865167	13	13	10	26
256	8	Product #5	Part #11/Part #12/Part #13/Part #14	1 1 1 1 1 1 1 1 1 1 1 1 1		1.0678E+19	12	TRUE	0.554991196	0	9	7	20
128	7	Product #11	Part #28/Part #29/Part #30/Part #31	1 1 1 1 1 1 1 1 1 1 1		9.22345E+18	13	TRUE	0.01493297	0	0	0	0
64	6					0	14	TRUE		0	0	0	0
32	5					0	14	TRUE		0	0	0	0
16	4					0	14	TRUE		0	0	0	0
8	3					0	14	TRUE		0	0	0	0
4	2					0	14	TRUE		0	0	0	0
2	1					0	14	TRUE		0	0	0	0
1	0					0	14	FALSE		0	0	0	0

Tool Changeovers		11
Tool Changeover Time	00:07.5	
Total Tool Changeover Time	0:23:08	

Decimal Equivelent	# 0 0 0 0
Rank	1 2 3 4 5 6 8 # 6 # # 9 # # # # # # # # # # # #
Ordered?	# #
Ordered?	1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	12	12	12	12	12	12	11	12	12	12	12	12	11.91666667	11	12
Initial Total Tool Changeover Time	0:27:23	0:29:00	0:28:45	0:30:45	0:29:30	0:29:00	0:26:08	0:30:22	0:31:00	0:30:07	0:29:22	0:27:00	0:29:02	0:26:08	0:31:00
Tool Changeovers	11	12	12	12	12	12	12	11	12	12	11	11	11.66666667	11	12
Total Tool Changeover Time	0:22:23	0:25:22	0:25:53	0:24:30	0:27:00	0:25:22	0:24:15	0:24:00	0:24:22	0:25:07	0:24:22	0:23:08	0:24:39	0:22:23	0:27:00
Tool changover delta	1	0	0	0	0	0	-1	1	0	0	1	1	0.25	-1	1
Tool Changeover Time Savings	0:05:00	0:03:37	0:02:52	0:06:15	0:02:30	0:03:37	0:01:53	0:06:22	0:06:37	0:05:00	0:05:00	0:03:53	0:04:23	0:01:53	0:06:37

Minimum
0:22:23

Tools - Product Line C - Unpaired

Binary Value: # # # # # … # 8 4 2 1

Part #s\Tools / Previous Jobs: 1 1 1 1 1 1 1 1

Binary Value		Part #s\Tools	Tool marks	Decimal Euivelent	Rank	Oredered?	Random Numbers	Number of Tools For 2 Tables	Removed Attached	Total Tools Used for chageover
5.5E+11	39	Part #20	1 1 1 1	1.38351E+20	1	TRUE	0.587444074	6	6	12
2.75E+11	38	Part #17	1 1 1 1	1.17598E+20	2	TRUE	0.355757871		4	10
1.37E+11	37	Part #18	1 1 1	7.55164E+19	3	TRUE	0.799992274	7	3	0
6.87E+10	36	Part #13	1 1 1 1	5.57726E+19	4	TRUE	0.468797607		4	12
3.44E+10	35	Part #26	1 1 1	1.8807E+19	5	TRUE	0.97029004	7	5	0
1.72E+10	34	Part #24	1 1 1 1	6.97157E+18	6	TRUE	0.112605771		5	19
8.59E+09	33	Part #7	1 1 1 1 1 1	6.93442E+18	7	TRUE	0.940526463	15	4	0
4.29E+09	32	Part #11	1 1 1 1 1 1 1 1 1 1 1 1	4.66235E+18	8	TRUE	0.290413322		12	22
2.15E+09	31	Part #12	1 1 1 1	4.6297E+18	9	TRUE	0.691161628	10	12	0
1.07E+09	30	Part #28	1 1 1 1 1 1	3.45933E+18	10	TRUE	0.451220383		7	15
5.37E+08	29	Part #30	1 1 1	2.31485E+18	11	TRUE	0.727709697	7	8	0
2.68E+08	28	Part #14	1 1 1 1 1 1	2.30613E+18	12	TRUE	0.334103395		5	8
1.34E+08	27	Part #27	1 1 1	2.30585E+18	13	TRUE	0.999272066	3	5	0
67108864	26	Part #4	1 1 1	2.30585E+18	13	TRUE	0.264403718		1	8
33554432	25	Part #1	1 1 1 1	1.8735E+18	15	TRUE	0.839876432	5	3	0
16777216	24	Part #9	1 1 1	1.80144E+18	16	TRUE	0.038710613		5	12
8388608	23	Part #5	1 1 1	1.80144E+18	16	TRUE	0.021199928	10	2	0
4194304	22	Part #2	1 1 1 1 1 1 1 1	5.78853E+17	18	TRUE	0.557854714		7	17
2097152	21	Part #23	1 1 1 1	2.89356E+17	19	TRUE	0.773934051	7	10	0
1048576	20	Part #19	1 1 1 1	2.8823E+17	20	TRUE	0.160806529		7	15
524288	19	Part #21	1 1 1 1	2.8823E+17	21	TRUE	0.97473867	11	4	0
262144	18	Part #29	1 1 1 1 1 1 1	3.82822E+16	22	TRUE	0.896397896		8	20
131072	17	Part #22	1 1 1 1 1 1	4.5036E+15	23	TRUE	0.84859181	10	10	0
65536	16	Part #3	1 1 1 1	2.25181E+15	24	TRUE	0.118422218		9	19
32768	15	Part #16	1 1 1 1 1 1 1	2.81595E+14	25	TRUE	0.987559439	9	10	0
16384	14	Part #6	1 1 1 1 1 1 1	2.81544E+14	26	TRUE	0.638812111		9	13
8192	13	Part #8	1 1 1 1	33554656	27	TRUE	0.551623476	4	9	0
4096	12	Part #10	1 1 1 1	33554656	27	TRUE	0.98499449		4	9
2048	11	Part #25	1 1 1	8388632	29	TRUE	0.715140513	6	4	0
1024	10	Part #15	1 1 1	7	30	TRUE	0.626985773		6	0
512	9			0	31	TRUE		0	0	0
256	8			0	31	TRUE			0	0
128	7			0	31	TRUE		0	0	0
64	6			0	31	TRUE			0	0
32	5			0	31	TRUE		0	0	0
16	4			0	31	TRUE			0	0
8	3			0	31	TRUE		0	0	0
4	2			0	31	TRUE			0	0
2	1			0	31	TRUE		0	0	0
1	0			0	31	FALSE			0	0

Decimal Equivelent: # # # # # … #
Rank: 1 2 3 4 5 6 7 8 9 # # … #
Ordered?: 1 1 1 1 … 1 1 0

Radom Numbers: 1 0 0 1 0 0 1 1 1 1 0 0 1 1 1 1 1 0 1 0 0 0 1 0 0 1 1 1 0 1 0 1 0 1 1 0 0 1 1 0 1 1 0 1 0 1 1 0 0 1 1 0 0 1 1 0 1 1 1 1 0 1 1 0 0 1 0

Total Tool Changeove	0:23:30
Tool Changeover Tim	00:07.5
Tool Changeovers	8
Changeovers	15

Minumum
0:20:45

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	13	15	11	13	14	12	12	14	13	12	13	15	13.08333333	11	15
Initial Changeover Time	0:28:30	0:30:00	0:28:00	0:31:07	0:28:15	0:28:07	0:30:00	0:27:00	0:25:37	0:27:23	0:29:00	0:30:00	28:35.0	25:37.5	31:07.5
Tool Changeovers	8	8	9	9	7	10	9	7	10	8	9	8	8.5	7	10
Changeover Time	0:20:45	0:21:15	0:23:08	0:23:08	0:23:37	0:23:37	0:23:00	0:22:30	0:23:15	0:22:45	0:23:08	0:23:30	22:48.1	20:45.0	23:37.5
Tool Changeover Savings	5	7	2	4	7	2	3	7	3	4	4	7	4.583333333	2	7
Changeover Time Savings	0:07:45	0:08:45	0:04:52	0:08:00	0:04:37	0:04:30	0:07:00	0:04:30	0:02:22	0:04:38	0:05:52	0:06:30	05:46.9	02:22.5	08:45.0

Tools - Product Line C - Paired

Binary Value		Products(s)	Part#s\Tools	Tools (binary columns)
			Binary Value	# 8 4 2 1
				# 9 8 7 6 5 4 3 2 1 0
Binary Value			Part#s\Tools	3 1 4 2 9 5 3 5 1 1 5 3 1 # 7 1 2 1 1 1 1 4 1 1 9 5 1 # 8 1 1 1 3 1 3 .5 9 2 1 5 1 # 3 5 5 7 1 1 1 8 3 3 1 1 1 4 3 5 5 1 1 3 # 1 9 1 1/2 END MILL
		Products(s)	Previous Jobs	1 1 1 1 1 1 1 1 1 1 1 1 1 1
524288	19	Product #7	Part #25/Part#26	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
262144	18	Product #10	Part #35/Part#36/Part#37/Part #38	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
131072	17	Product #3	Part #10/Part#11/Part#12/Part #13	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
65536	16	Product #4	Part #14/Part#15/Part#16	1 1 1 1 1 1 1 1 1 1 1 1 1 1
32768	15	Product #6	Part #21/Part#22/Part#23/Part #24	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
16384	14	Product #5	Part #17/Part#18/Part#19/Part #20	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8192	13	Product #1	Part# 1/ Part #2/Part #3/Part #5	1 1 1 1 1 1 1 1 1 1
4096	12	Product #8	Part #27/Part#28/Part#29/Part #30	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
2048	11	Product #9	Part #31/Part#32/Part#33/Part #34	1 1 1 1 1 1 1
1024	10	Product #2	Part #6/Part#7/Part#8/Part #9	1 1 1 1 1 1 1 1 1 1 1 1
512	9			
256	8			
128	7			
64	6			
32	5			
16	4			
8	3			
4	2			
2	1			
1	0			

Decimal Equivelent	# #
Rank	1 2 3 4 5 6 7 8 9 #
Ordered?	# #
Ordered?	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
Random Numbers	1 0 1 0 1 1 0 0 0 1 0 1 1 0 0 0 0 0 0 0 1 0 1 1 1 0 1 1 0 0 1 1 0 0 1 0 1 1 1 1 0 1 1 0 1 0 0 1 0 0 0 0 0 0 1 1 0 1 0 0 1 1 1 1 0 0

Decimal Equiv	Rank	Orderec	Random Number	Tools	Removed	Attached	Total Tools Used in changeover
1.47574E+20	1	TRUE	0.317680964	19	10	14	29
1.10681E+20	2	TRUE	0.27523458	16	17	14	33
1.01457E+20	3	TRUE	0.628850853	16	6	6	22
9.68456E+19	4	TRUE	0.253984678	14	11	9	25
2.19056E+19	5	TRUE	0.763569462	15	13	14	28
2.07528E+19	6	TRUE	0.918180709	15	10	10	25
9.22342E+18	7	TRUE	0.078351618	10	12	7	22
7.78242E+18	8	TRUE	0.611215487	16	7	13	23
7.49418E+18	9	TRUE	0.514927919	7	9	0	16
5.49804E+13	10	TRUE	0.410297849	0	5	5	12
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	TRUE		0	0	0	0
0	11	FALSE		0	0	0	0

Tool Changeovers		9
Tool Changeover Time	00:07.5	
Total Tool Changeover Time	0:24:00	

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	10	9	9	10	9	9	10	10	10	10	10	10	9.6666667	9	10
Initial Total Tool Changeover Time	0:26:15	0:25:15	0:27:30	0:26:22	0:27:08	0:25:22	0:26:00	0:24:45	0:27:15	0:24:45	0:24:52	0:24:45	0:25:51	0:24:45	0:27:30
Tool Changeovers	10	10	10	9	9	10	10	10	10	9	10	9	9.6666667	9	10
Total Tool Changeover Time	0:23:00	0:24:52	0:24:30	0:23:30	0:23:23	0:24:45	0:23:37	0:23:45	0:24:37	0:26:38	0:25:37	0:24:00	0:24:21	0:23:00	0:26:38
Tool changover delta	0	-1	-1	1	0	-1	0	0	0	1	0	1	0	-1	1
Tool Changeover Time Savings	0:03:15	0:00:22	0:03:00	0:02:53	0:03:45	0:00:37	0:02:22	0:01:00	0:02:38	########	########	0:00:45	0:01:30	#########	0:03:45

Minimum
0:23:00

Fixtures - Product Line A - Unpaired

		Binary Value	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
			66	65	64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41
		Part # \ Fixture #	37	##	##	##	92	##	46	52	63	64	48	44	13	##	99	91	##	35	##	47	16	65	36	14	98	##
Binary Value		Last Job															1											
5.49756E+11	39	Part #15	1																									
2.74878E+11	38	Part #29		1																								
1.37439E+11	37	Part #2			1																							
68719476736	36	Part #5			1																							
34359738368	35	Part #27				1																						
17179869184	34	Part #17					1																					
8589934592	33	Part #18						1																				
4294967296	32	Part #6						1																				
2147483648	31	Part #9							1																			
1073741824	30	Part #4								1																		
536870912	29	Part #11									1	1																
268435456	28	Part #28											1															
134217728	27	Part #1												1														
67108864	26	Part #3													1													
33554432	25	Part #22													1													
16777216	24	Part #14														1												
8388608	23	Part #12															1											
4194304	22	Part #21																1										
2097152	21	Part #24																	1									
1048576	20	Part #7																		1								
524288	19	Part #23																			1							
262144	18	Part #26																				1						
131072	17	Part #10																					1					
65536	16	Part #8																						1				
32768	15	Part #16																							1			
16384	14	Part #30																								1		
8192	13	Part #25																								1		
4096	12	Part #13																								1		
2048	11	Part #19																									1	
1024	10	Part #20																										1
512	9																											
256	8																											
128	7																											
64	6																											
32	5																											
16	4																											
8	3																											
4	2																											
2	1																											
1	0																											
		Decimal Equivelent	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
		Rank	1	2	3	4	5	6	7	8	9	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
		Ordered?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Radom Numbers	0	0	1	0	1	1	1	0	0	1	0	1	0	0	1	1	1	0	0	0	1	0	1	0	1	0

Binary Value	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	64	32	16	8	4	2	1
	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Decimal Equivelent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rank	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Ordered?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Decimal Euivelent	Rank	Oredered?	Random Numbers	Sum	Less shared Fixtures
7.3787E+19	1	TRUE	0.27269569	1	1
3.68935E+19	2	TRUE	0.193954968	1	1
1.84467E+19	3	TRUE	0.612351561	1	1
1.84467E+19	3	TRUE	0.398800603	1	0
9.22337E+18	5	TRUE	0.963224898	1	1
4.61169E+18	6	TRUE	0.806717864	1	1
2.30584E+18	7	TRUE	0.175071137	1	1
2.30584E+18	7	TRUE	0.709476822	1	0
1.15292E+18	9	TRUE	0.190643129	1	1
5.76461E+17	10	TRUE	0.285943036	1	1
4.32346E+17	11	TRUE	0.462005783	1.5	1.5
7.20576E+16	12	TRUE	0.757612331	1.5	1.5
3.60288E+16	13	TRUE	0.026962809	1	1
1.80144E+16	14	TRUE	0.835403785	1	1
1.80144E+16	14	TRUE	0.712317632	1	0
9.0072E+15	16	TRUE	0.025404916	1	1
4.5036E+15	17	TRUE	0.713462759	1	1
2.2518E+15	18	TRUE	0.16899072	1	1
1.1259E+15	19	TRUE	0.189779034	1	1
5.6295E+14	20	TRUE	0.340592201	1	1
2.81475E+14	21	TRUE	0.807754738	1	1
1.40737E+14	22	TRUE	0.077204779	1	1
7.03687E+13	23	TRUE	0.314289909	1	1
3.51844E+13	24	TRUE	0.985357867	1	1
1.75922E+13	25	TRUE	0.860595042	1	1
8.79609E+12	26	TRUE	0.281383317	1	1
8.79609E+12	26	TRUE	0.261111652	1	0
8.79609E+12	26	TRUE	0.040579538	1	0
4.39805E+12	29	TRUE	0.699127495	1	1
2.19902E+12	30	TRUE	0.139704843	1	1
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	TRUE		0	0
0	31	FALSE		0	0

Fixture Changeover Time	0:03:05
Total Fixture Changeover Time	1:20:10

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial	1:30:57	1:35:35	1:35:35	1:32:30	1:32:30	1:35:35	1:35:35	1:35:35	1:35:35	1:35:35	1:32:30	1:32:30	1:34:10	1:30:57	1:35:35
Fixture Changeover Time	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10	1:20:10
Savings	0:10:48	0:15:25	0:15:25	0:12:20	0:12:20	0:15:25	0:15:25	0:15:25	0:15:25	0:15:25	0:12:20	0:12:20	0:14:00	0:10:48	0:15:25

Minimum
1:20:10

Fixtures - Product Line A - Paired

Binary Values	# 8 4 2 1
	# 9 8 7 6 5 4 3 2 1 0

Binary Values		Product(s)	Part # \ Fixture #	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
			Last Job										1	1															
524288	#	Product #17	Part #28/Part #29	1	1																								
262144	#	Product #5/Product #6	Part #7/Part #8/Part	1		1																							
131072	#	Product #18	Part #30/Part #31		1		1																						
65536	#	Product #4	Part #5/Part #6			1		1	1	1																			
32768	#	Product #21	Part #36/Part #37			1					1																		
16384	#	Product #15	Part #24/Part #25				1					1																	
8192	#	Product #1/Product #2	Part #1/Part #2				1						1																
4096	#	Product #9	Part #14/Part #15					1						1															
2048	#	Product #7	Part #10/Part #11					1							1														
1024	#	Product #23	Part #40/Part #41										1			1													
512	9	Product #10	Part #16/Part #17														1	1											
256	8	Product #12/Product #13	Part #20/Part #21																1	1									
128	7	Product #14	Part #22/Part #23																1		1								
64	6	Product #20	Part #34/Part #35																			1	1						
32	5	Product #3	Part #3/Part #4																			1		1					
16	4	Product #11	Part #18/Part #19																			1			1				
8	3	Product #22	Part #38/Part #39																			1				1			
4	2	Product #19	Part #32/Part #33																			1					1		
2	1	Product #8	Part #12/Part #13																			1						1	
1	0	Product #16	Part #26/Part #27																			1							1

Decimal Equivelent	# 8 4 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Rank	1 2 3 4 5 6 6 8 9 #
Ordered?	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
Random Numbers	0 0 0 1 0 1 1 0 0 1 1 1 0 0 0 0 1 0 0 1 0 0 1 1 1 0

Decimal Equive	Rank	Ordere	Random Number	Sum	Less Shared Fixtures
1.1068E+20	1	TRUE	0.615539391	2	2
9.22337E+19	2	TRUE	0.071395684	2	1
4.61169E+19	3	TRUE	0.425628282	2	2
2.65172E+19	4	TRUE	0.657638261	3	3
1.90232E+19	5	TRUE	0.175717703	3	2
9.5116E+18	6	TRUE	0.316811251	2	2
9.36749E+18	7	TRUE	0.7358409	2	1
4.68374E+18	8	TRUE	0.341461758	2	2
4.64771E+18	9	TRUE	0.295064819	2	1
1.6213E+17	10	TRUE	0.122330084	2	2
1.35108E+16	11	TRUE	0.641026565	2	2
3.3777E+15	12	TRUE	0.745007148	2	2
2.81475E+15	13	TRUE	0.973827362	2	1
4.22212E+14	14	TRUE	0.170655392	2	2
3.51844E+14	15	TRUE	0.860095654	2	1
3.16659E+14	16	TRUE	0.574201166	2	1
2.99067E+14	17	TRUE	0.904709604	2	1
2.90271E+14	18	TRUE	0.710639473	2	1
2.85873E+14	19	TRUE	0.66294834	2	1
2.83674E+14	20	FALSE	0.159313064	2	1
				42	31

Fixture Changeover Time	0:03:05
Total Fixture Changeover Time	1:35:35

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Fixture Changeover Time	1:51:00	2:00:15	1:54:05	1:57:10	1:44:50	1:54:05	1:47:55	1:57:10	1:57:10	1:54:05	1:57:10	1:54:05	1:54:05	1:44:50	2:00:15
Fixture Changeover Time	1:23:15	1:35:35	1:23:15	1:35:35	1:23:15	1:29:25	1:26:20	1:35:35	1:23:15	1:35:35	1:29:25	1:35:35	1:29:40	1:23:15	1:35:35
Time Savings	0:27:45	0:24:40	0:30:50	0:21:35	0:21:35	0:24:40	0:21:35	0:21:35	0:33:55	0:18:30	0:27:45	0:18:30	0:24:25	0:18:30	0:33:55

Minimum
1:23:15

Fixtures - Product Line B - Unpaired

Binary Value # 8 4 2 1
9 8 7 6 5 4 3 2 1 0

Part #s\Fixture #s #

Previous Job 1

Binary Value		Part		Decimal Equivelent	Rank	Oredered?	Random Numbers	Sum	Less shared Fixtures
5.49756E+11	39	Part #5	1	7.3787E+19	1	TRUE	0.067481723	1	1
2.74878E+11	38	Part #7	1	3.68935E+19	2	TRUE	0.233206253	1	1
1.37439E+11	37	Part #15	1	3.68935E+19	2	TRUE	0.504988617	1	0
68719476736	36	Part #19	1	1.84467E+19	4	TRUE	0.61323152	1	1
34359738368	35	Part #23	1	1.84467E+19	4	TRUE	0.181752952	1	0
17179869184	34	Part #21	1	9.22337E+18	6	TRUE	0.231164864	1	1
8589934592	33	Part #17	1	4.61169E+18	7	TRUE	0.325948372	1	1
4294967296	32	Part #13	1	4.61169E+18	7	TRUE	0.473517745	1	0
2147483648	31	Part #28	1	2.30584E+18	9	TRUE	0.305616779	1	1
1073741824	30	Part #26	1	1.15292E+18	10	TRUE	0.953716203	1	1
536870912	29	Part #4	1	5.76461E+17	11	TRUE	0.91222149	1	1
268435456	28	Part #9	1	2.8823E+17	12	TRUE	0.886033038	1	1
134217728	27	Part #20	1	1.44115E+17	13	TRUE	0.120137243	1	1
67108864	26	Part #10	1	1.44115E+17	13	TRUE	0.658742116	1	0
33554432	25	Part #1	1	7.20576E+16	15	TRUE	0.704928524	1	1
16777216	24	Part #16	1	3.60288E+16	16	TRUE	0.530722036	1	1
8388608	23	Part #2	1	1.80144E+16	17	TRUE	0.379884535	1	1
4194304	22	Part #18	1	9.0072E+15	18	TRUE	0.831135364	1	1
2097152	21	Part #11	1	4.5036E+15	19	TRUE	0.064459772	1	1
1048576	20	Part #27	1	4.5036E+15	19	TRUE	0.708730272	1	0
524288	19	Part #22	1	2.2518E+15	21	TRUE	0.171382752	1	1
262144	18	Part #6	1	1.1259E+15	22	TRUE	0.90823082	1	1
131072	17	Part #14	1	1.1259E+15	22	TRUE	0.139232352	1	0
65536	16	Part #24	1	5.6295E+14	24	TRUE	0.012593833	1	1
32768	15	Part #12	1	2.81475E+14	25	TRUE	0.692987065	1	1
16384	14	Part #3	1	1.40737E+14	26	TRUE	0.37000792	1	1
8192	13	Part #8	1	7.03687E+13	27	TRUE	0.424969132	1	1
4096	12	Part #25	1	3.51844E+13	28	TRUE	0.5415834	1	1
2048	11			0	29	TRUE		0	0
1024	10			0	29	TRUE		0	0
512	9			0	29	TRUE		0	0
256	8			0	29	TRUE		0	0
128	7			0	29	TRUE		0	0
64	6			0	29	TRUE		0	0
32	5			0	29	TRUE		0	0
16	4			0	29	TRUE		0	0
8	3			0	29	TRUE		0	0
4	2			0	29	TRUE		0	0
2	1			0	29	TRUE		0	0
1	0			0	29	FALSE		0	0

Decimal Equivelent # 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Rank 1 2 3 4 5 6 7 8 9 #
Ordered? 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0

Radom Numbers 1 0 0 0 0 1 1 1 1 1 1 0 1 1 1 0 1 1 1 0 0 0

Fixture Changeover Time	0:03:05
Total Fixture Changeover Time	1:07:50

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial	1:26:20	1:23:15	1:23:15	1:26:20	1:23:15	1:26:20	1:23:15	1:26:20	1:26:20	1:26:20	1:23:15	1:26:20	1:25:03	1:23:15	1:26:20
Fixture Changeover Time	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50	1:07:50
Savings	0:18:30	0:15:25	0:15:25	0:18:30	0:15:25	0:18:30	0:15:25	0:18:30	0:18:30	0:18:30	0:15:25	0:18:30	0:17:13	0:15:25	0:18:30

Minimum
1:07:50

Fixtures - Product Line B - Paired

			Binary Value	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	8	4	2	1
				66	65	64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	9	8	7	6	5	4	3	2	1	0
			Part #s/Tools	74	72	95	##	56	55	##	##	54	##	##	75	73	##	##	##	15	##	79	90	78	89																																															
Binary Value			Previous Job			1									1																																																									
524288	#	Product #11	Part #25/Part #26/Part #27/Part #28	1	1	1	1																																																															
262144	#	Product #9	Part #19/Part #20	1				1																																																														
131072	#	Product #15	Part #39/Part #40	1					1																																																												
65536	#	Product #7	Part #13/Part #14/Part #15/Part #16		1					1	1	1																																																										
32768	#	Product #1/Product #2	Part #1/Part #2/Part #3/Part #4		1								1	1																																																								
16384	#	Product #13	Part #33/Part #34					1							1																																																						
8192	#	Product #4	Part #7/Part #8						1							1																																																				
4096	#	Product #10	Part #21/Part #22/Part #23/Part #24							1							1	1																																																				
2048	#	Product #5/Product #6	Part #9/Part #10/Part #11/Part #12								1								1	1	1																																																	
1024	#	Product #8	Part #17/Part #18								1								1	1																																																	
512	9	Product #12	Part #29/Part #30/Part #31/Part #32												1		1																																																			
256	8	Product #14	Part #35/Part #36/Part #37/Part #38													1						1	1	1																																												
128	7	Product #3	Part #5/Part #6														1								1																																												
64	6																																																																						
32	5																																																																						
16	4																																																																						
8	3																																																																						
4	2																																																																						
2	1																																																																						
1	0																																																																						
			Decimal Equivelent	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Rank	1	2	3	3	5	6	7	8	9	10	10	12	13	14	15	16	16	18	19	19	19	22	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
			Ordered?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
			Random Numbers	0	1	0	0	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	1	1	0																																																			

Decimal Equiv	Rank	Ordered?	Random Number	Sum	Less Shared Tools
1.38351E+20	1	TRUE	0.348058839	3	2
7.83987E+19	2	TRUE	0.971935545	3	2
7.60928E+19	3	TRUE	0.264157365	2	1
3.89111E+19	4	TRUE	0.681869521	3	3
3.71097E+19	5	TRUE	0.164825036	3.5	2.5
4.64771E+18	6	TRUE	0.766821245	2.5	2.5
2.32386E+18	7	TRUE	0.733815761	2	2
1.16643E+18	8	TRUE	0.722545445	2.5	2.5
5.80401E+17	9	TRUE	0.2599698	3.5	3.5
5.79838E+17	10	TRUE	0.973504368	3.5	0.5
4.5036E+16	11	TRUE	0.452806915	2.5	2.5
1.8507E+16	12	TRUE	0.444531503	3	3
9.04238E+15	13	TRUE	0.41330978	3	3
0	14	TRUE		0	0
0	14	TRUE		0	0
0	14	TRUE		0	0
0	14	TRUE		0	0
0	14	TRUE		0	0
0	14	TRUE		0	0
0	14	FALSE		0	0
				37	30
			Fixture Changeover Time	0:03:05	
			Total Fixture Changeover T	1:32:30	

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Fixture Changeover Time	1:44:50	1:49:27	1:47:55	1:37:07	1:43:17	1:47:55	1:41:45	1:44:50	1:44:50	1:47:55	1:44:50	1:35:35	1:44:11	1:35:35	1:49:27
Fixture Changeover Time	1:23:15	1:32:30	1:32:30	1:23:15	1:26:20	1:20:10	1:23:15	1:27:53	1:26:20	1:29:25	1:26:20	1:32:30	1:26:59	1:20:10	1:32:30
Time Savings	0:21:35	0:16:57	0:15:25	0:13:52	0:16:58	0:27:45	0:18:30	0:16:57	0:18:30	0:18:30	0:18:30	0:03:05	0:17:13	0:03:05	0:27:45

Minimum
1:20:10

Fixtures - Product Line B - Unpaired

Binary Value: # # # … # 8 4 2 1 / # # # … # 9 8 7 6 5 4 3 2 1 0

Part #s\Tools: 43 3/ 5N 1/ 4N 10 9/ 1/ 1/ 9/ 12 2" 13 5/ 3/ 7/ 5.: 11 3/ 10 1/ 29 1/ #2 11 2- 10 4N 1/ 1.! 18 #7 1/ .5(9/ 1- #2 14 3/ 5/ 3/ 9/ 5/ 5.! 1/ 1/ 5.: 1/ 1-: 3/ 1-! 8.: 1/ 8-: 3.! 3.! #7 1/ 7.(11 5/ 3/ 1/ 16 3/ 1" C"SI

Previous Jobs: 1 1 1 1 1 1 1

Binary Value		Part #s\Tools	Tools (1 = used)	Decimal Euivelent	Rank	Oredered?	Random Numbers	Number of Tools For 2 Tables	Removed Attached	Total Tools Used for chageover
5.5E+11	39	Part #20	1 1 1 1	1.38351E+20	1	TRUE	0.587444074	6	6	12
2.75E+11	38	Part #17	1 1 1 1	1.17598E+20	2	TRUE	0.355757871		4	10
1.37E+11	37	Part #18	1 1 1	7.55164E+19	3	TRUE	0.799992274	7	3	0
6.87E+10	36	Part #13	1 1 1 1	5.57726E+19	4	TRUE	0.468797607		4	12
3.44E+10	35	Part #26	1 1 1	1.8807E+19	5	TRUE	0.97029004	7	5	0
1.72E+10	34	Part #24	1 1 1 1	6.97157E+18	6	TRUE	0.112605771		5	19
8.59E+09	33	Part #7	1 1 1 1 1 1	6.93442E+18	7	TRUE	0.940526463	15	4	0
4.29E+09	32	Part #11	1 1 1 1 1 1 1 1 1 1 1 1	4.66235E+18	8	TRUE	0.290413322		12	22
2.15E+09	31	Part #12	1 1 1 1	4.6297E+18	9	TRUE	0.691161628	10	12	0
1.07E+09	30	Part #28	1 1 1 1 1 1	3.45933E+18	10	TRUE	0.451220383		7	15
5.37E+08	29	Part #30	1 1 1	2.31485E+18	11	TRUE	0.727709697	7	8	0
2.68E+08	28	Part #14	1 1 1 1 1 1	2.30613E+18	12	TRUE	0.334103395		5	8
1.34E+08	27	Part #27	1 1 1	2.30585E+18	13	TRUE	0.999272066	3	5	0
67108864	26	Part #4	1 1 1	2.30585E+18	13	TRUE	0.264403718		1	8
33554432	25	Part #1	1 1 1 1	1.8735E+18	15	TRUE	0.839876432	5	3	0
16777216	24	Part #9	1 1 1	1.80144E+18	16	TRUE	0.038710613		5	12
8388608	23	Part #5	1 1 1	1.80144E+18	16	TRUE	0.021199928	10	2	0
4194304	22	Part #2	1 1 1 1 1 1 1 1	5.78853E+17	18	TRUE	0.557854714		7	17
2097152	21	Part #23	1 1 1 1	2.89356E+17	19	TRUE	0.773934051	7	10	0
1048576	20	Part #19	1 1 1 1	2.8823E+17	20	TRUE	0.160806529		7	15
524288	19	Part #21	1 1 1 1	2.8823E+17	21	TRUE	0.97473867	11	4	0
262144	18	Part #29	1 1 1 1 1 1 1	3.82822E+16	22	TRUE	0.896397896		8	20
131072	17	Part #22	1 1 1 1 1 1	4.5036E+15	23	TRUE	0.84859181	10	10	0
65536	16	Part #3	1 1 1 1	2.25181E+15	24	TRUE	0.118422218		9	19
32768	15	Part #16	1 1 1 1 1 1	2.81595E+14	25	TRUE	0.987559439	9	10	0
16384	14	Part #6	1 1 1 1 1 1	2.81544E+14	26	TRUE	0.638812111		9	13
8192	13	Part #8	1 1 1 1	33554656	27	TRUE	0.551623476	4	9	0
4096	12	Part #10	1 1 1 1	33554656	27	TRUE	0.98499449		4	9
2048	11	Part #25	1 1 1	8388632	29	TRUE	0.715140513	6	4	0
1024	10	Part #15	1 1 1	7	30	TRUE	0.626985773		6	0
512	9			0	31	TRUE		0	0	0
256	8			0	31	TRUE			0	0
128	7			0	31	TRUE		0	0	0
64	6			0	31	TRUE			0	0
32	5			0	31	TRUE		0	0	0
16	4			0	31	TRUE			0	0
8	3			0	31	TRUE		0	0	0
4	2			0	31	TRUE			0	0
2	1			0	31	TRUE		0	0	0
1	0			0	31	FALSE			0	0

Decimal Equivelent: #

Rank: 1 2 3 4 5 6 7 8 9 #

Ordered?: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0

Radom Numbers: 1 0 0 1 0 0 1 1 1 1 0 0 1 1 1 1 1 0 1 0 0 0 1 0 0 1 1 1 0 1 0 1 0 1 1 0 0 1 1 0 1 1 0 1 0 1 1 0 0 1 1 0 0 1 1 0 1 1 1 1 0 1 1 0 0 1 0

Total Tool Changeove	0:23:30
Tool Changeover Tim	00:07.5
Tool Changeovers	8
Changeovers	15

Minumum
0:20:45

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Tool Changeovers	13	15	11	13	14	12	12	14	13	12	13	15	13.08333333	11	15
Initial Changeover Time	0:28:30	0:30:00	0:28:00	0:31:07	0:28:15	0:28:07	0:30:00	0:27:00	0:25:37	0:27:23	0:29:00	0:30:00	28:35.0	25:37.5	31:07.5
Tool Changeovers	8	8	9	9	7	10	9	7	10	8	9	8	8.5	7	10
Changeover Time	0:20:45	0:21:15	0:23:08	0:23:08	0:23:37	0:23:37	0:23:00	0:22:30	0:23:15	0:22:45	0:23:08	0:23:30	22:48.1	20:45.0	23:37.5
Tool Changoever Savings	5	7	2	4	7	2	3	7	3	4	4	7	4.583333333	2	7
Changeover Time Savings	0:07:45	0:08:45	0:04:52	0:08:00	0:04:37	0:04:30	0:07:00	0:04:30	0:02:22	0:04:38	0:05:52	0:06:30	05:46.9	02:22.5	08:45.0

Fixtures - Product Line C - Paired

Binary Value
8 4 2 1
9 8 7 6 5 4 3 2 1 0

Binary Value			Tools/Part #s	#	5	7	#	#	#	1	#	#	#	#	#	#	#	#	#	M	M	#	M	#	#	#	#	#	#
			Previous Job											1			1				1							1	
524288	#	Product #1	Part #1/Part #2/Part #3/Part #4	1	1	1	1																						
262144	#	Product #10	Part #26/Part #27					1	1	1																			
131072	#	Prduct #7/Product #8	Part #19/Part #20/Part #21/Part #22/Part #23/Part #24								1	1	1	1															
65536	#	Product #11	Part #28/Part #29								1				1	1	1	1											
32768	#	Product #3/Product #4	Part #9/Part #10/Part #11/Part #12								1								1	1	1	1							
16384	#	Product #12/Product #13	Part #30/Part #31/Part #32/Part #33								1												1						
8192	#	Product #15	Part #38/Part #39/Part #40/Part #41																1	1									
4096	#	Product #14	Part #34/Part #35/Part #36/Part #37																		1			1					
2048	#	Product #5/Product #6	Part #13/Part #14/Part #15/Part #16/Part #17/Part #18																				1		1				
1024	#	Product #2	Part #5/Part #6/Part #7/Part #8																							1	1	1	1
512	9	Product #9	Part #24/Part #25																							1	1	1	1
256	8																												
128	7																												
64	6																												
32	5																												
16	4																												
8	3																												
4	2																												
2	1																												
1	0																												

Decimal Equivelent: # 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Rank: 1 1 1 1 5 5 5 8 9 9 9 #
Ordered?: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0

Random Numbers: 1 1 1 1 0 1 1 0 0 0 1 1 1 1 0 1 0 1 1 0 0 1 1 1 0 0

Decimal Equivelent	Rank	Ordered?	Random Number	Sum	Less Shared Fixtures
1.38351E+20	1	TRUE	0.239228977	4	4
8.07045E+18	2	TRUE	0.725240819	3.5	3.5
1.08086E+18	3	TRUE	0.522154248	3.5	3.5
6.44015E+17	4	TRUE	0.549132741	4.5	3.5
5.80683E+17	5	TRUE	0.44011876	5	4
5.76601E+17	6	TRUE	0.830000531	3.5	2.5
3.3777E+15	7	TRUE	0.658132424	2	2
6.33319E+14	8	TRUE	0.975385847	2	2
1.75922E+14	9	TRUE	0.412863763	2	2
3.29853E+13	10	TRUE	0.346509879	3	3
3.29853E+13	10	TRUE	0.423979524	4	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	TRUE		0	0
0	12	FALSE		0	0
				37	30

Fixture Changeover Time 0:03:05
Total Fixture Changeover T 1:32:30

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Average	Min	Max
Initial Fixture Changeover Time	1:30:57	1:51:00	1:43:17	1:44:50	1:38:40	1:46:23	1:51:00	1:46:23	1:29:25	1:54:05	1:44:50	1:49:27	1:44:11	1:29:25	1:54:05
Fixture Changeover Time	1:27:53	1:23:15	1:30:57	1:30:57	1:29:25	1:29:25	1:29:25	1:26:20	1:30:57	1:29:25	1:32:30	1:32:30	1:29:25	1:23:15	1:32:30
Time Savings	0:03:05	0:27:45	0:12:20	0:13:52	0:09:15	0:16:57	0:21:35	0:20:03	######	0:24:40	0:12:20	0:16:57	0:14:46	######	0:27:45

Minimum
1:23:15

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