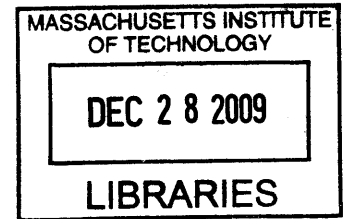# Head & Base Production Optimization:
Setup Time Reduction

by
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B.Eng., Mechanical Engineering
Shanghai Jiao Tong University, 2007

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in Manufacturing

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ABSTRACT

At Schlumberger, the make-to-order strategy and number of Head & Base product types (about 1000 types) requires a flexible manufacturing system in which the machine setup is frequent. However, the lengthy CNC machine setup time in the Head & Base machining station directly affects the manufacturing capacity. This research implements Single Minute Exchange of Die (SMED) methodology and proposes a set of solutions, such as manufacturing sequence optimization, setup sequence optimization, setup operation simplification, etc, to reduce setup time without sacrificing quality. Most of the solutions have been implemented and the result is significant and impressive, the overall setup time has been reduced by up to 40 percent and the expected cost saving is about 50,000 USD.

Keywords:

Lean, Setup time, Head & Base, CNC machine, SMED, Sequence

Thesis Supervisor: Kamal Youcef-Toumi

Title: Professor, Department of Mechanical Engineering

ACKNOWLEDGEMENT

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1 Introduction

1.1 Project introduction

This research took place at Schlumberger Limited (SLB) in Singapore. At Schlumberger, one of the most critical problems is that the existing production rate cannot meet the customer demands and the lead time is not satisfactory to the customer. This project was focused on improving the production rate as well as reducing lead time for Head and Base, which is one key component for all the final products in Schlumberger.

One main problem regarding the production rate lies in long setup time in the machining station. The other problem is related to the long lead time wasted in the improper inventory management. This project is divided into two parts aiming at solving these two problems respectively: one is about the setup time reduction and the other is about inventory management optimization. This thesis focuses on the first part of this project.

The main objective of research described here is to reduce the setup time of CNC machine without sacrificing quality and to improve output and productivity of the whole machining station.

1.2 Company background

Schlumberger Limited (SLB) is the world's leading oilfield services company supplying technology, information solutions and integrated project management that optimize reservoir performance for customers working in the oil and gas industry. Founded in 1926, today the company employs more than 87,000 people working in approximately 80 countries.

The company was founded by the two Schlumberger brothers who invented wireline logging as a technique for obtaining downhole data in oil and gas wells. Today, it continues to build on the industry's longest track record of providing leading edge

Exploration and Production (E&P) technology to develop new advancements-from reservoir to surface.

Singapore Integration center (SPE) is one of Schlumberger's largest research, development and manufacturing plants for electric submersible pumps (ESPs), downhole pressure/temperature gauges and gas lift mandrels (GLMs). It is a 550,000 square foot plant and has a full set of manufacturing operations, from foundry works producing castings for pumps, a large machine-shop to machine all the component parts, an assembly-shop and full Quality Control testing facilities.

The total workforce is more than 700 including more than 70 professionals (designers, engineers) in Engineering, Manufacturing, Sustaining who are focused on continuous improvements and new product development of SPE's products.

SPE adopts a make-to-order manufacturing model due to the nature of its products. Most of the orders are then sold to internal customers such as Schlumberger's field services and other manufacturing centers.

1.3 Product

The major products produce in SPE are electric submersible pumps (ESPs), which include a motor, pump, protector and gas separator/intake. ESP systems have a wide range of applications and offer an efficient and economical lift method.

To ensure a competitive advantage above the market's competitors, Schlumberger also provides monitoring systems, surface electrical equipment, engineering services, and optimization services to complement the ESP system. By integrating technology and service, Schlumberger successfully provides an optimum lift system for the well and optimize pump and well performance while reducing operating costs.

The four major products are illustrated in Figure 1-1. Detailed structure is simplified for confidential purpose. These products are then assembled into full functional ESP at customer's site.
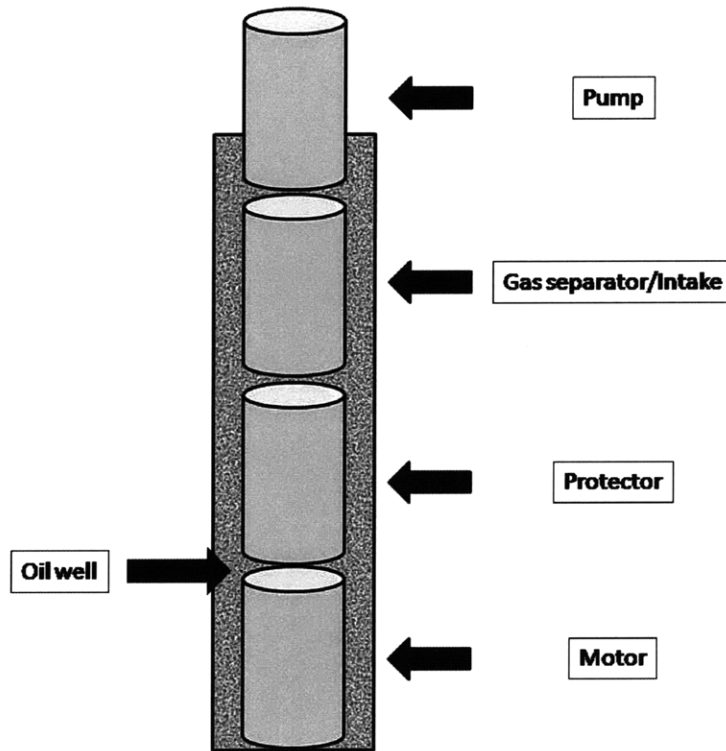
Figure 1-1 Final assembled ESP

In the manufacturing process, basic components are first manufactured and then assembled into four major products. For economical and convenient reason, basic components are categorized into housing, shaft, head & base, thrust bearing, bar part, stage, and rotor. General steps regarding the manufacturing process for the four basic units include casting, machining, subassembly, etc. Details are shown in Figure 1-2 Process map of ESP manufacturing.
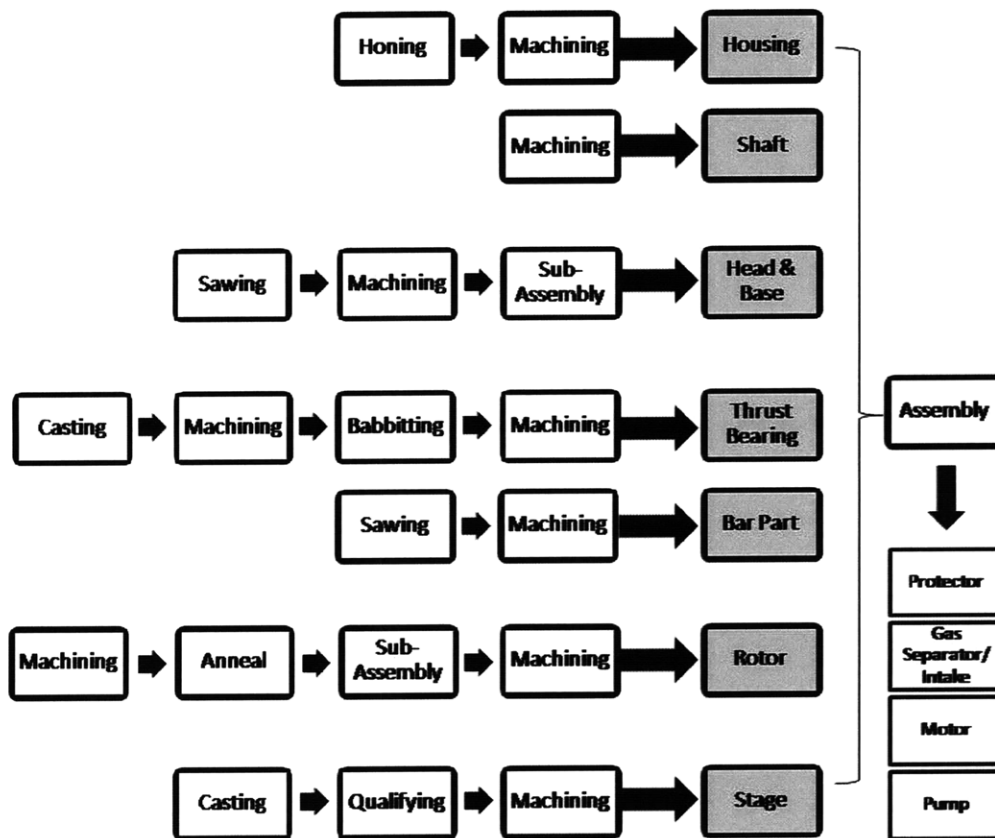
Figure 1-2 Process map of ESP manufacturing

In this research, the main focus is in the manufacturing of Head and Base (H&B). H&B part is one of the key components for all the final products. Each pump, motor, protector, and intake requires at least one H&B. The factory manufactures more than 1000 different types of H&B, which is subject to the large amount of product types.

2 Problem Statement

2.1 Introduction

This chapter first describes the current process flow and value stream map (VSM) of H&B manufacturing; then discusses some problems the H&B department is facing, analyzes the root cause of the problems. Lastly, we choose one significant problem as the focusing area of our research and define its scope and objective.

2.2 Current production flow

Before this research officially starts, a value stream map (in APPENDIX A) is finished in order to help staff involved in this research have a background knowledge about situation in H&B manufacturing process. Takt time in each station is calculated and listed in Table 2-1.

Table 2-1 Takt time in each station

Station	1	2	3	4	5	6	7
Takt Time (min)	8.43	9.04	3.16	4.22	10.0	3.34	6.66

From Figure 2-1, station 5 (subassembly station) requires the most Takt time to finish one work piece, followed by station 2 (machining station). However, by checking the VSM in APPENDIX A, it turns out that the setup time (C/O) in station 2 makes its situation even worse: machining station uses Takt time which is far more than that in subassembly station in reality.
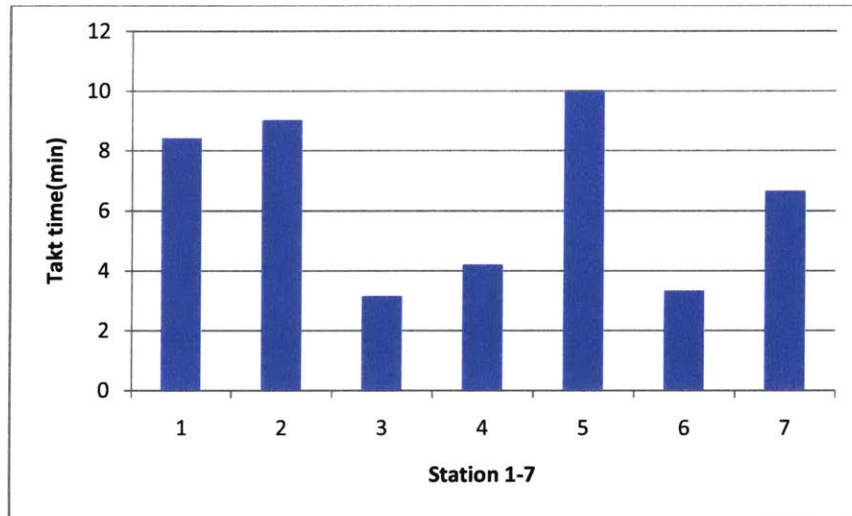
Figure 2-1 Takt time distribution in 7 stations for H&B manufacturing process

Three major steps are included in the VSM for the H&B manufacturing process. Between these three steps and equipment assembly, the parts go to warehouse twice for storage or buffer purpose. A simplified process flow is illustrated in Figure 2-2.
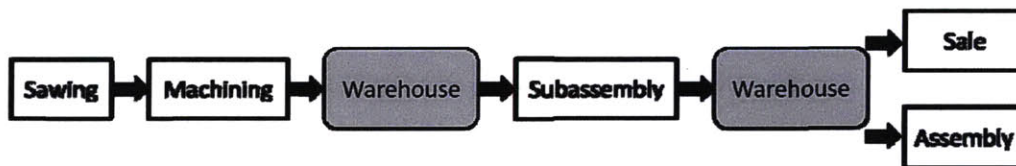
Figure 2-2 Head & Base process flow

At the sawing station, raw material (long bar part) is cut into short work piece; then the short work pieces are sent to the machining station to be machined into detailed parts. After the inspectors check the detailed parts, these parts are then sent to the warehouse, waiting for subassembly process. In the subassembly station, detailed parts, as well as components, are assembled together to make the functional H&B products, some of which are sent to equipment assembly while the others are sent to service center for direct part sale.

After examining the current process flow, we identified two problems: the lengthy setup time in machining station affects the manufacturing capacity; the improper material inventory management increases the lead time. Details about these two problems will be illustrated below respectively.

Firstly, setup is the process of changing the machine configuration from producing one part to another. The setup time is calculated as the time from finished the last piece of previous batch to finished the first piece of the current batch. This time includes material preparation time, tool change time, tool calibration time, as well as extra rework and inspection time. At Schlumberger H&B machining station, the typical setup time is about four hours, while the machining time for one piece is one hour. The average setup frequency is once per day; thus the setup time is about 20% of the total production time.

The long setup time affects the machining capacity directly. In order to meet customer demands with the existing machining capacity, the company has no way but to outsource some work orders to contractors, which incurs much higher cost, increases the lead time and makes quality control more difficult.

Moreover, the long setup time also affects the company's overall production strategy. Although Schlumberger tries to adopt a make-to-order strategy, the planner has to combine orders with the same part in order to reduce setup frequency. This practice then increases work in process (WIP), which requires more inventories holding cost.

Secondly, the current lead time from sawing station to issuing sub-assembled parts to equipment assembly is 24 days, which is far more than the actual processing time (2.5 hours only). As mentioned above, the long setup time and large amount of WIP are two reasons for the long lead time. Another reason is that the parts go into and come out of warehouse several times, which increases the complexity of the process and thus the lead time. Moreover, the receiving process in warehouse is tedious and fatiguing. Most importantly, all these materials need to wait for a long time in waiting area to be handled by operators, largely because of lacking of workforce. Besides the warehouse receiving

and issuing, the information flow also contributes to the long lead time. After the parts are received or issued by the warehouse, the work order needs to be sent to the clerk to update the system, which takes few hours or sometimes an entire day to finish.

2.3 Scope and objective

This thesis focuses on the first problem, the long setup time problem as described above and aims at reducing this long setup time. In the setup time reduction part of this project, the project team needs to look into solving the limited machining capacity problem by reducing setup time without sacrificing quality.

The main objective of this project is to reduce the setup time of machine without increasing scrap rate and improve output and productivity of the whole machining station. In H&B machining station, there are in total eight cells in work. CNC machines in cell 5, 6 and 7 are more complex when compared with machines in other cells so that the setup time for these machines is much longer than that for the other. This provides more potential to make improvements. Therefore, this project will focus on setup time reduction for cell 5, 6 and 7. The current goal of this project is to reduce the setup time by 30%. Extension to other cells will be implemented at the end of this year if the trials for cell 5, 6 and 7 succeed.

2.4 Summary

In sum, there are two major problems in the head and base production process: the lengthy setup time in machining station affects the manufacturing capacity; the improper material inventory management increases the lead time. This thesis focuses on reducing the setup time in H&B machining station.

3 Literature Review

3.1 Introduction

This chapter will first review literature on Lean Manufacturing development and approaches and the definition of waste. The knowledge of Single Minute Exchange of Die (SMED), which is one of the many Lean production methods for reducing waste in a manufacturing process, is brought out to help solve problems in the setup time reduction project. Then this chapter will review literature on SMED concept, its development and advantages. At last, this project will review the Schlumberger basic project roadmap which our research will follow.

3.2 Lean manufacturing

Lean manufacturing or Lean production is a production practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination. In 1991, James P. Womack first defined Lean manufacturing is a generic process management philosophy derived mostly from the Toyota Production System (TPS) [1].The main focus of Lean is to optimize flow by increasing efficiency, decreasing waste and empirically digging out the problems. Lean principles come from the Japanese manufacturing industry. The term was first coined by John Krafcik in a Fall 1988 article, "Triumph of the Lean Production System," published in the Sloan Management Review and based on his master's thesis at MIT. [2]

There are basically two approaches to Lean Manufacturing. One is to take Lean as a set of tools that assist in the identification and elimination of waste. The elimination of waste helps improve quality and reduce production time and cost. Examples of such tools are Value Stream Mapping, Five S, Kanban, and poka-yoke. The other focuses on improving the smoothness of work, thereby steadily eliminating unevenness through the process. Techniques to improve the smoothness include production leveling, Kanban and the Heijunka box.

In this research, we mainly choose the waste elimination approach in which the primary work is to distinguish the waste from normal manufacturing process.

Ohno then defined three types of waste: muda (non-value-adding work), muri (overburden), and mura (unevenness). This ever finer clarification of waste is the key to establishing distinctions between value-adding activity, waste and non-value-adding work [3]. Taiichi Ohno further specified the waste into seven detailed categories [4]:

- Transportation (moving products that are not actually required to perform the processing)
- Inventory (all components, work-in-progress and finished product not being processed)
- Motion (people or equipment moving or walking more than is required to perform the processing)
- Waiting (waiting for the next production step)
- Overproduction (production ahead of demand)
- Over Processing (due to poor tool or product design creating activity)
- Defects (the effort involved in inspecting for and fixing defects)

This clear definition of waste is important and it made the success of TPS possible. It also provides us instructive guidance in distinguishing waste for the Schlumberger project and therefore opportunity for improvement. Most importantly, clear identification of where waste may lie also provides opportunity for breakthroughs in SMED, JIT and other process changing techniques.

3.3 Single Minute Exchange of Die

Single Minute Exchange of Die (SMED) is one of the many Lean production methods for reducing waste in a manufacturing process. It provides a rapid and efficient way of converting a manufacturing process from running the current product to running the next product. This rapid changeover is helpful in reducing production lot sizes and thereby improving flow. It is also often referred to as Quick Changeover (QCO). Performing

faster changeovers is important in manufacturing, or any process, because they make low cost flexible operations possible.

The SMED concept is created by engineer Shigeo Shingo, one of the main contributors to the consolidation of the Toyota Production System, along with Taiichi Ohno. From the past experience, the overhead costs of retooling a process were minimized by maximizing the number of items that the process should construct before changing to another model. This makes the changeover overhead per manufactured unit low. According to some sources optimum lot size occurs when the interest costs of storing the lot size of items equals the value lost when the production line is shut down. [5]

Engineer Shingo pointed out if the changeover time could be reduced, then the economic lot size could be reduced, directly reducing expenses. Shingo also stated that large lot sizes require higher stock levels to be kept in the rest of the process and these, more hidden costs, are also reduced by the smaller lot sizes made possible by SMED. Over a period of several years, Toyota reworked factory fixtures and vehicle components to maximize their common parts, minimize and standardize assembly tools and steps, and utilize common tooling. These common parts or tooling reduced changeover time. Wherever the tooling could not be common, steps were taken to make the tooling quick to change.

Setup	N°	Possible						
Actual	1	Yes	60	360				
Actual	3	No	60	120	60	120	60	120
Improved	3	No		120		120		120
			30		30		30	
Optimize	5	No	72	72	72	72	72	
			12	12	12	12	12	
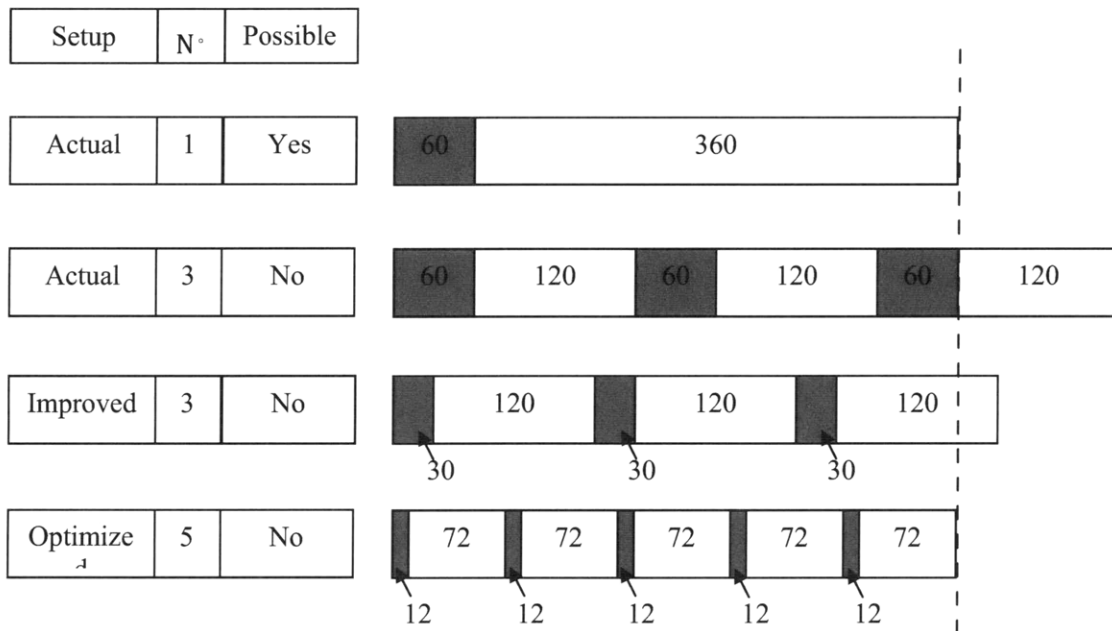
Figure 3-1 Advantage of SMED concept

Advantage of the SMED concept is illustrated in Figure 3-1, which includes four successive runs with learning from each run and improvements applied before the next.

Run 1 shows the original situation. Run 2 shows what would happen if more changeovers were included. Run 3 shows the impact of the improvements in changeover times. Run 4 shows how these improvements can get you back to the same production time but now with more flexibility in production capacity. All these above are sufficient to indicate that setup time reduction provides potential for a flexible manufacturing system within the existing manufacturing capacity.

During the implementation of the SMED, Shigeo Shingo recognized eight techniques [6] that should be considered.
1. Separate internal from external setup operations
2. Convert internal to external setup
3. Standardize function, not shape
4. Use functional clamps or eliminate fasteners altogether

5. Use intermediate jigs
6. Adopt parallel operations
7. Eliminate adjustments
8. Mechanization

In general, the idea behind the SMED methodology is to convert internal operations to external operations. This approach is beneficial when the team has someone available to prepare the external elements while the machine is operating. This method is highly recommended to reduce changeover time, thereby allowing extra production time to increase output or build in smaller batches. [7]

3.4 Basic project roadmap

Generally, there are five basic steps in the Lean Six Sigma project roadmap: definition, measurement, analysis, improvement and control. Detailed steps description regarding this project are listed and illustrated below:

In the definition step, communication with people like manager, operator, planner and etc is necessary and will help better understand the exiting problem in the company. After collecting enough relative information, the scope and objective can be defined and process mapping can be finished.

Measurement not only refers to the activity of collecting quantitative data but also means observation. In measurement for setup, data such as time used for each step is recorded for later analysis; and wastes, shortages, mistakes, inadequate verification of equipment causing delays should be identified and recorded during observation. After that, baseline measures of the current process should be established and objectives in order to gauge improvement success must be set.

The analysis step includes analyzing the collected data, uncovering the potential root causes of the problem by using data analysis, process mapping analysis, cause and effect, and prioritizing down to the ones that have the biggest impact on the problem. If possible,

adequate simulation, regression and multi-variance analysis can be completed to find those variables that of highest effect on the desired response.

The task of the improvement step is to generate all the possible solutions; prioritize and select the optimum solution from all possible solutions. After implementation, measurements on the setup time must be taken again in order to accomplish project objectives and statistically validate the effectiveness of the improvement.

At the end of the project, it is required that the project is under control. Project team need to standardize the improved actions and sustain the results over time. Because of time limitation, some portion of this step can be defined as future work. Also, after the project is finished, project team should ensure communication and sharing the best practices with others, identifying the future improvement needs for the area.

Among all these steps, measurement is the step deserves the most concern. In particular, machine and operator waiting time directly affects the capacity of the cell. Any non-value-added behavior which contributes to waiting time is taken as waiting and should be eliminated. Also, the moving or walking of operator or equipment more than is required to perform the processing should be grouped and analyzed. Due to poor or insufficient tool, there is some over-processing which can be avoided by providing the right tool. The measurement step requires finding out these wastes and grouping them accordingly.

3.5 Summary

Therefore, Head & Base production optimization project will take into account of Lean Manufacturing; and in setup time reduction project, it will focus on SMED method by looking at eight basic techniques proposed by Shingo. At last, this research is required to follow the Schlumberger Lean Six Sigma basic project roadmap.

4 Methodology

4.1 Introduction

This chapter will first summarize the detailed steps for implementing the SMED. Then this chapter will introduce the setup data collected regarding setup time, operations and movements. Cause and effect of the problem will be found out in the data analysis and then all the possible solutions will be proposed.

4.2 SMED steps

Some detailed methods for implementing SMED have already been developed by Greg Lane [7]. According to the special situation in this research, we developed a characterized method by taking reference of Greg Lane's theory.

Firstly, we determined whether implementing SMED was appropriate for this project. To help make this determination, the primary consideration is if there is short of capacity, bottleneck or long lead time in the process. Moreover, the optimum changeover also requires little adjustments to the first few parts manufactured after setup, little machine idle time while the first part is quality-checked and the documentation completed. If the observation indicates that the setup is not optimum, it sees the potential to implement SMED.

Secondly, we observed the setup by using the following methods: videotaping operator's movement, drawing a spaghetti diagram, listing and timing all elements completed by the operator. During setup, there were three basic items need to be reviewed: planning,

tooling and working method. Thirdly, we distinguished the internal and external elements during setup and then identified the internal that could become external. The next step was to convert internal elements to external elements by starting with those that could be moved to external without significant cost. At last, we simplified all setup operations in order to reduce the unnecessary time further.

4.3 Data collection

4.3.1 General machine parameter

In this project, we analyze setup process for CNC machines in cell 5, 6 and 7. Machine name and model in each cell is listed in Table 4-1.

Table 4-1 Machine list

Cell	Machine	Model
Cell 5	MAZATROL	IG 200
Cell 6	MAZATROL	E 410
Cell 7	DMG	TWIN 500

Although different in brand and model, the basic functional structures of these CNC machines are similar to each other. All CNC machines in Schlumberger use three-jaw chuck, a rotating clamp which uses three dogs or jaws, usually interconnected via a scroll gear, to hold onto work piece. Turrets including the designated tools are stored in the tool box inside CNC machine. The drawing for general CNC machine structure is shown in Figure 4-1. Specially, for CNC machines in cell 6 and 7, each one has two chucks which enable the CNC machine to process two work pieces at the same time. This advantage, on the other hand, requires more setup time since the amount of the jaws and tools needed to be changed has almost been doubled.
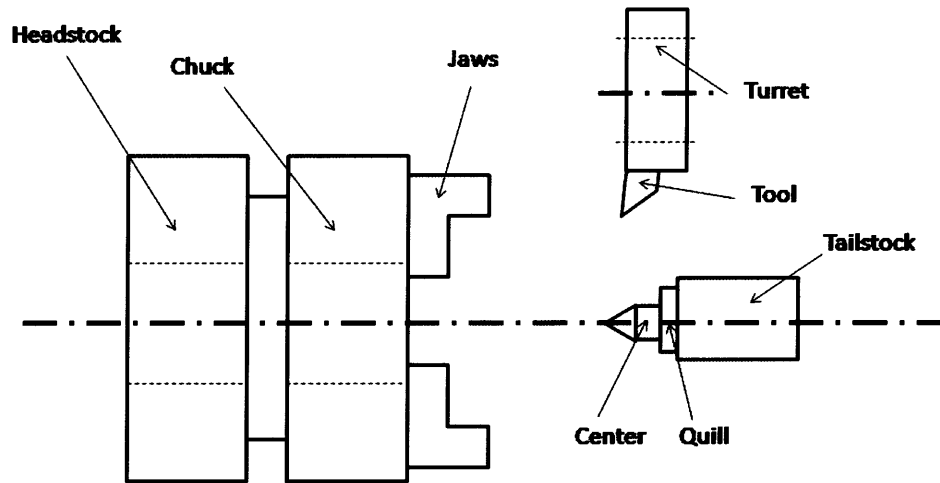
Figure 4-1 CNC machine structure drawing

Data needed to be collected includes setup time, setup operation elements and setup movements. These data are served as reference for improvement and evaluation.

4.3.2 Setup time

This project only uses historical record in 2008 as baseline. Mean value and standard deviation for the setup time is calculated and listed in Table 4-2.

Table 4-2 Setup time in 2008 for Cell 5, 6 and 7

Setup Time	Cell 5	Cell 6	Cell 7
Mean (hr)	2.99	3.75	4.12
Standard deviation (hr)	1.24	1.44	1.73

On average, setup time in cell 6 and 7 is much higher than that in cell 5, partially because of the double chuck structure in cell 6 and 7 stated above. Histograms of setup time for cell 5, 6 and 7 before improvement (in 2008) are listed from Figure 4-2 to Figure 4-4.
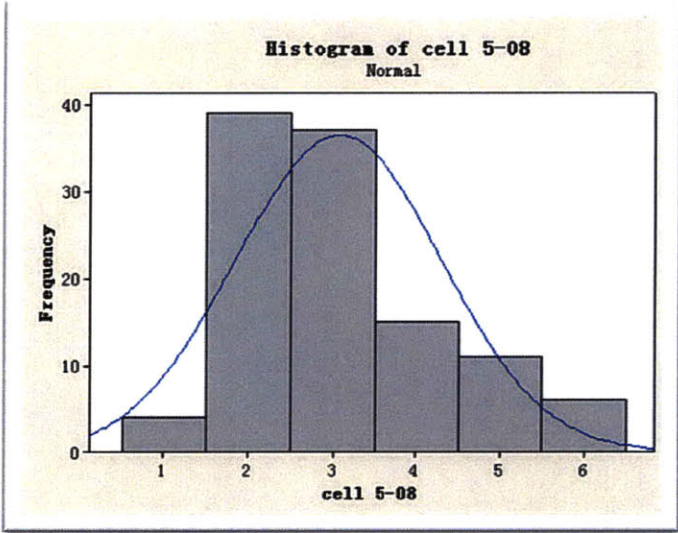
Figure 4-2 Histogram of setup time for cell 5 in 2008
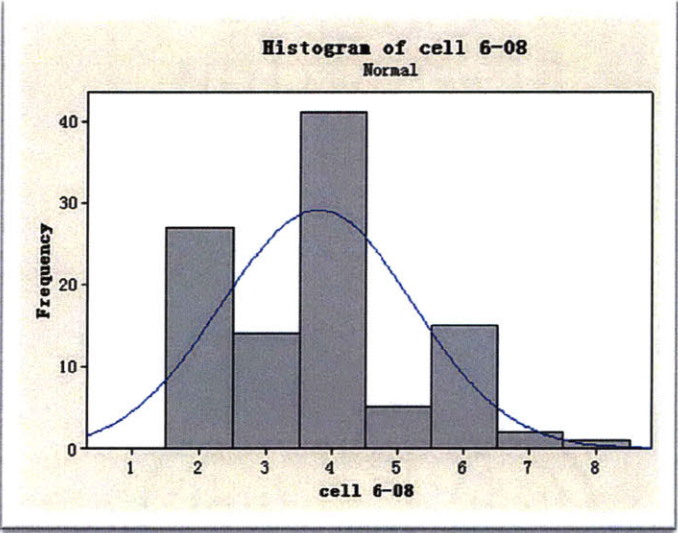
Figure 4-3 Histogram of setup time for cell 6 in 2008
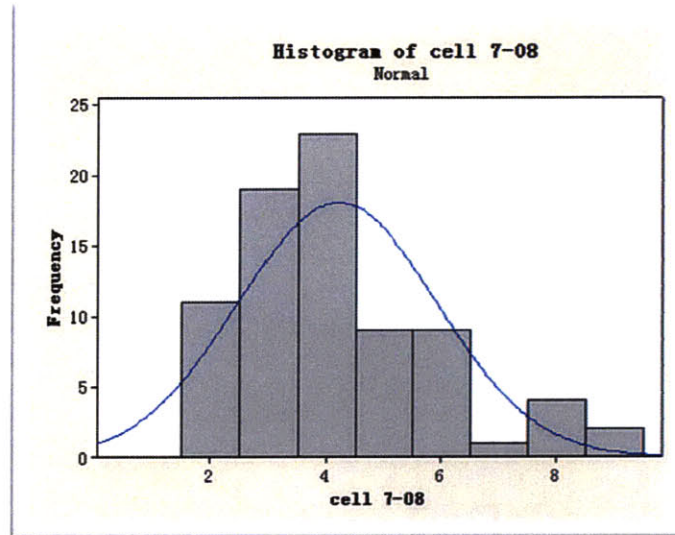
Figure 4-4 Histogram of setup time for cell 7 in 2008

As shown in the histograms, setup time data generally follows a normal distribution. Three main factors contribute to the high variance shown in the histograms above: work piece type difference, lack of standardized procedure and operator experience difference. Machine failure also affects the setup time; however, it is inconsequential since machine failure is not a frequent phenomenon during setup.

4.3.3 Setup operation elements

The setup procedure can be divided into four basic elements: preparation, jaw change, tool change, the 1st part machining.

Preparation phase is used to prepare the raw material, jaw and tools for the setup. Tool change phase includes insert change and holder change. In tool change, tool eye inspection is only required for the changed tool used for finishing cut; changed tool used

for rough cut does not have such requirement. Because the offset of the newly changed tool is not accurate, frequent inspection and rework is required for machining the 1st part besides normal machining. Details about the setup operation elements are listed below.

1. Preparation
   - Raw material preparation
   - Jaw Preparation
   - Tool Preparation
2. Jaw change
3. Tool change
   - Insert change
   - Holder change
   - Tool eye inspection
4. The 1st part machining
   - Normal machining
   - Inspection
   - Rework

These elements do not necessarily follow a fixed sequence. In most cases, the operators randomly arrange these elements according to their habits. The most commonly used operation sequence and the average time for each operation are listed in Table 4-3.

Table 4-3 Operation sequence and average time

No.	Operations	Time (min)
	Machining last batch	
1	Raw material preparation	15
2	Jaw preparation	5
3	Jaw change	20
4	Tool preparation	20
5	Insert change	15
6	Holder change	15
7	Tool eye inspection	20
8	Machining	60
	Inspection	15
	Rework	40
	Total	225

The 8th step in Table 4-3 includes machining, inspection and rework. In setup, CNC machine needs to be stopped time after time for inspection purposes. Operators adjust the parameter in CNC machine accordingly and do rework to get the desired dimension.

4.3.4 Setup movements

The Spaghetti diagram is used to record the operator's movements during setup. This is a direct way to reflect the complexity of the setup procedure and rationality of the cell layout. In this project, movement with distance less than 2 foot is seen as insignificant and thus ignored. Figure 4-5 shows the spaghetti diagram for setup in CNC machine (cell 6) before improvement.
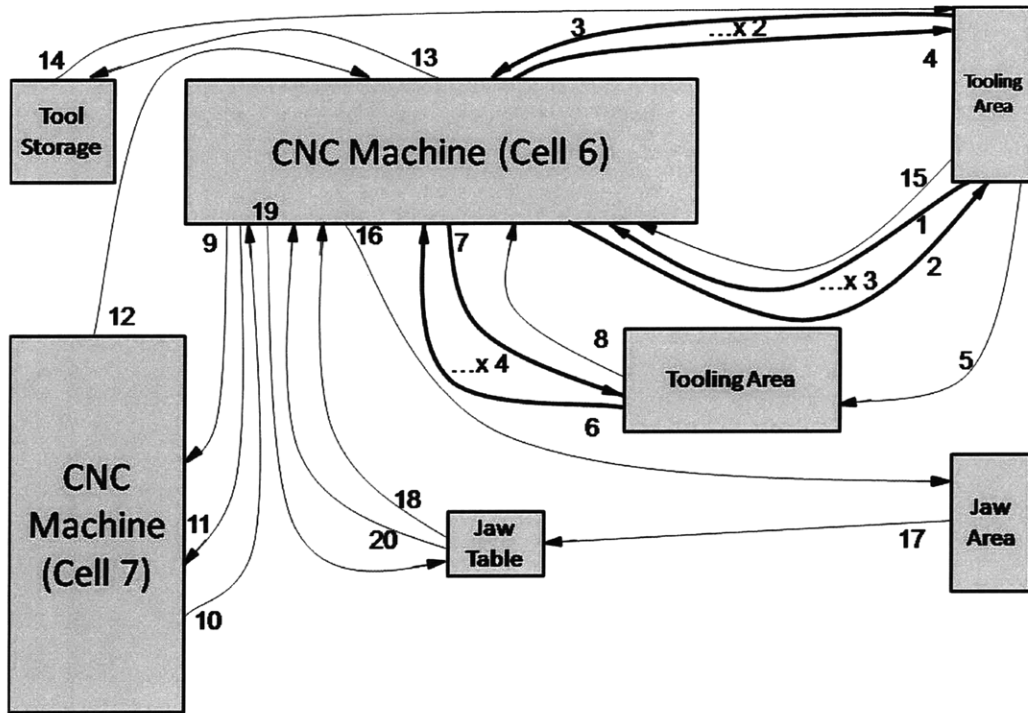
Figure 4-5 Spaghetti Diagram for setup in Cell 6 before improvement

Movements are denoted by curved lines with arrow showing the direction and number showing the sequence. In order to simplify the spaghetti diagram, those continuously repeating back and forth movements are denoted by bold curved lines. "…× n" indicates the times of that repeating back and forth movements.

This diagram tends to exhibit a disorder and illogical operator movement, in which the operator sometimes moves aimlessly without performing value-added action or searches around failing to find the right tool.

4.4 Data analysis

The purpose of data analysis is to find out the cause and effect of the problem we are aiming to solve. According to the Ishikawa diagram definition proposed by Kaoru Ishikawa [8], causes and effects of the problem are classified into six categories: Machine, Method, Material, Maintenance, Man and Mother Nature (environment).

In this project, six cause and effect categories are altered to suit Schlumberger's situation. Only five categories (Machine, People, Environment, Material and Method) are implemented and detailed cause and effect are illustrated in Figure 4-6.
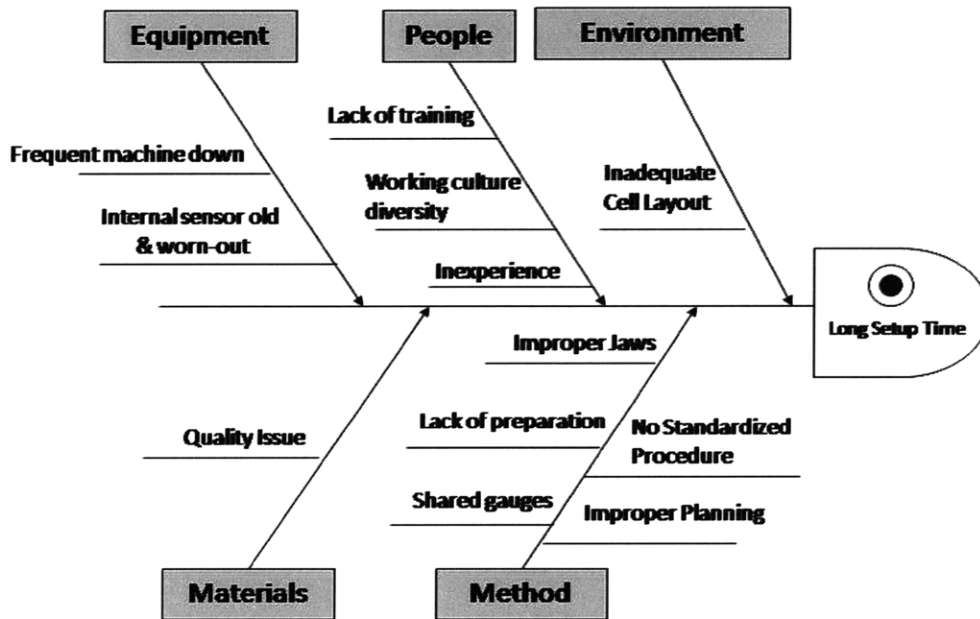
Figure 4-6 Cause and effect fishbone diagram

4.5 Improvement

According to the cause and effect analysis, all possible solutions are proposed, four of which are seen as the most profitable solutions and will be explained in detail. These solutions include manufacturing sequence optimization, setup sequence optimization, operation simplification (jaw change time reduction) and operation simplification (operator movement simplification).

4.5.1 Manufacturing sequence optimization

There is averagely daily setup for cell 5, 6 and 7 which means about 6 types of parts need to be manufactured per week in each cell. Manufacturing planner plans the manufacturing sequence for these 6 types of parts according to the customer order. Since manufacturing sequence greatly affects the tool change time and thus the total setup time, by designing an optimized manufacturing sequence, we plan to minimize the total changeover time.

The analysis for why the optimized manufacturing sequence can save time will be illustrated in detail below. In this analysis, we choose a simplified model which only involves 3 part types.

Tool change time is one important factor to the total setup time. For CNC machine, the tool can be classified as standard tool and optional tool. Standard tools are shared by all the parts and are not changed during setup. For different part type, optional tool needed might be different, and hereby a tool changed is required. In general, the similarity of the

optional tools determines the tool change time. The model in this thesis only considers the optional tool change.

The optional tools are labeled from 1 to 12. Each tool has more than one characterized tooling type. For example, tool 12A is different from tool 12B. Details about the simplified model are listed in Table 4-4.

Table 4-4 Simplified parts' optional tool list

Tool No.	Part 1	Part 2	Part 3
1		A	A
2			A
3			
4			B
5	A	A	A
6	A		A
7	C		C
8			D
9		E	
10			
11			B
12	B	A	B

In Table 4-4, there are three types of parts need to be manufactured. The total number of optional tools is 12. For example, part 1 needs optional tool 5A, 6A, 7C and 12B and part 2 needs optional tool 1A, 5A, 9E and 12A. If planner plans to manufacture part 1 first and then part 2 the next, there is a changeover after part 1 is finished and before part 2 begins. Operators should add tool 1A and 9E which are not included in the tool list for part 1; remove tool 6A and 7C which are not needed for part 2; and change tool 12B to 12A. On average, the time needed for removing one tool is 1 minute; the time needed for adding

one tool is 4 minutes; and the time needed for changing one tool (includes removing and

adding process) is 5 minutes.

Table 4-5 Operation time list

Operation	Time (min)
Change	5
Add	4
Remove	1

There are six possible manufacturing sequences for these three parts. Table 4-6shows all

the possible manufacturing sequences.

Table 4-6 Manufacturing sequences

Sequence No.	1st	2nd	3rd
1	Part 1	Part 2	Part 3
2	Part 1	Part 3	Part 2
3	Part 2	Part 1	Part 3
4	Part 2	Part 3	Part 1
5	Part 3	Part 1	Part 2
6	Part 3	Part 2	Part 1

The tool change time for each possible changeover can be calculated by the formula

below.

$$T_{tc} = n_c \cdot t_c + n_a \cdot t_a + n_r \cdot t_r$$

T_{tc} _the tool change time (from part to part)

n_c _the number of changed tools

n_a _the number of added tools

n_r _the number of removed tools

t_c _time to change one tool

t_a _time to add one tool

t_r _time to remove one tool

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The results of the calculation are arranged in a 3×3 matrix (Table 4-7). Tool change begins from part in the first column and to part in the first row. Time needed for tool change between same parts is zero.

Table 4-7 Tool change time matrix

	Part 1	Part 2	Part 3	To
Part 1	0	8	20	
Part 2	2	0	17	
Part 3	5	8	0	
From				

Therefore, for each possible manufacturing sequence, the total tool change time can be calculated. The results are list in Table 4-8.

Table 4-8 Manufacturing sequence and tool change time

No.	1st	2nd	3rd	Total Tool Change Time (min)
1	Part 1	Part 2	Part 3	25
2	Part 1	Part 3	Part 2	28
3	Part 2	Part 1	Part 3	22
4	Part 2	Part 3	Part 1	22
5	Part 3	Part 1	Part 2	13
6	Part 3	Part 2	Part 1	10

Apparently, sequence 6 (from part 3 to part 2 to part 1) costs the minimum tool change time (10 minutes) while sequence 2 (from part 1 to part 3 to part 2) costs the maximum tool change time (28 minutes). This tool change time reduction is significant when considering the changeover frequency in cell 5. Moreover, with the increase of the number of part types whose sequence needs to be arranged, the benefits can be more significant.

However, the manufacturing process in Schlumberger is based on the make-to-order strategy, which determines the manufacturing sequence size cannot be too large, even though a large manufacturing sequence size has more benefits as we have stated above. If the sequence size is too large, the optimized solution may suggest that one type of product should be manufactured at last, say two months later, for example, this so called optimized solution cannot be accepted by the customer since their order might get delayed. After discussing with manufacturing planner, the manufacturing sequence size is suggested to be 7 at most.

There are two main challenges in the practical application. Firstly, in the database, the Changeover Time Matrix is too complex to be completed manually. In Cell 5, there are 100 types of parts, which mean we need to develop a matrix with the size of 10,000 (100×100). Secondly, the process for selecting the optimized solution is complex. If we are required to arrange the manufacturing sequence for 7 types of parts, the number of possible solution is 5040 (factorial of 7). We need to calculate the total changeover time for these 5040 possible solutions respectively and choose the minimum one as optimum solution.

To solve these two problems, a convenient and functional program is required to be developed. We choose the Visual Basics language since it is compatible to Microsoft Excel which is used to store our database. Programming code is shown in Appendix B: VB Code (Matrix generation) and Appendix C: VB Code (Sequence optimization). The manufacturing planner, when using the program, selects at most 7 part types according to next week's schedule and the program will list all the possible manufacturing sequence,

calculate the overall tool change time respectively and select the optimum solution. All these can be finished in a few seconds.

4.5.2 Operation sequence optimization

The setup operation sequence before improvement has been explained. All steps can be categorized into either internal operation or external operation. External operation can be done without the process line being stopped whereas internal one needs the line to be stopped. By converting the internal operation into external operation, we can reduce the setup time to an ideal extent and therefore improve the efficiency of the operators.

In the previous setup sequence, the operator will not start setup until the last piece of the last batch is finished and the CNC machine stops. So, all operations are categorized into internal one. However, we see some potential for converting some of the internal operations into external ones. For example, tool preparation for the setup can be finished before the machine stops, so in the new category definition, tool preparation is be categorized into external operation. New operation category and old operation category are listed in Table 4-9 for comparison.

Table 4-9 Operation category

No.	Operations	Time (min)	Old Category	New Category
	Machining			
1	Raw material preparation	15	Internal	External
2	Jaw preparation	5	Internal	External
3	Jaw change	20	Internal	Internal
4	Tool preparation	20	Internal	External
5	Insert change	15	Internal	Internal
6	Holder change	15	Internal	Internal
7	Tool eye inspection	20	Internal	External
8	Machining	60	Internal	Internal
	Inspection	15		
	Rework	40		
	Total	225		
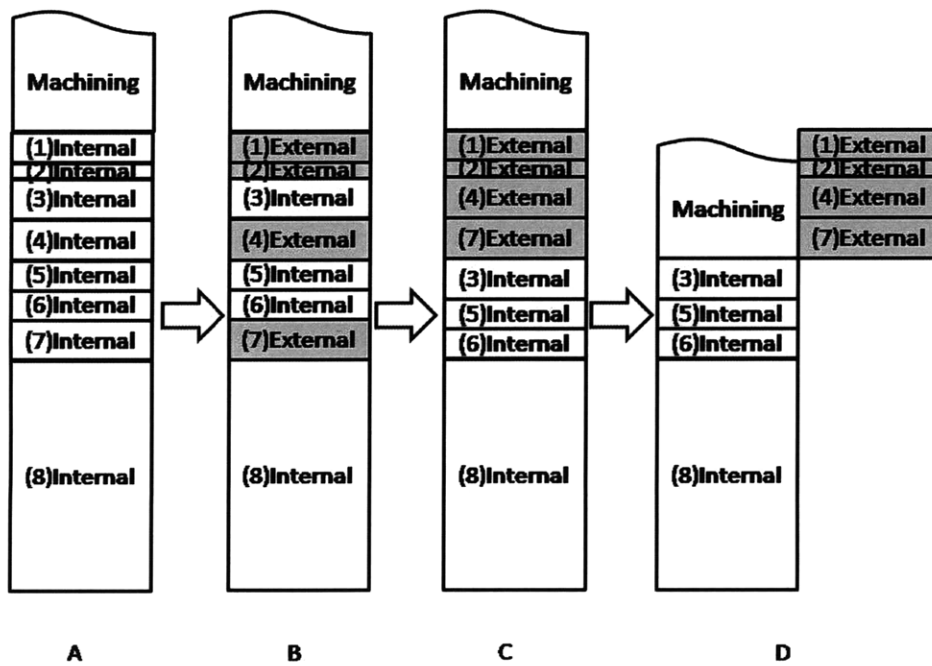
Figure 4-7 Setup operation sequence improvement

Figure 4-7 illustrates the details about the setup operation sequence improvement. Height of the operation block reflects the average operation time. The improvement procedure can be divided into four statuses.

Status A indicates the old setup operation sequence before improvement. Machining (the CNC machining process of the last batch) does not belong to the setup process. The bracketed numbers in Figure 4-7 accords with the operation sequence number indicated in Table 4-9.

In status B, the operations which can be converted from internal operation into external one are distinguished. Raw material preparation (operation 1), jaw preparation (operation 2) and tool preparation (operation 4) can be directly converted into external activities. Some of the conversion needs assistance from other operators or bringing in new equipments. For example, converting tool eye inspection (operation 7) can be achieved by bring in a new external measuring machine called tool master.

In status C, internal and external operations are separated. In status D, all the external activities are required to be finished before the CNC machine finishes the last batch. CNC machine provides opportunity for making this improvement. Previously, when CNC machine is automatically running, operators are required to make use of the human idle time (machine run time) to deburr, polish, etc. It is observed that operators still have much human idle time left even if they are designated with the deburr and polish work. Therefore, requiring operators to prepare raw material and tool during machine run makes better use of this human idle time.

The expected benefit of this improvement is time used for external operation can be removed from the machine setup time. Ideally, the time reduction is the sum of all external operations' time.

$$T(reduction) = t(external) = t(op.1) + t(op.2) + t(op.4) + t(op.7) = 60 \text{ min}$$

The next step after sequence improvement is to simplify the existing internal operations. Details about the operation simplification will be illustrated from subsection 5.4.3 to 5.4.6. General status regarding the simplification is shown in Figure 4-8.
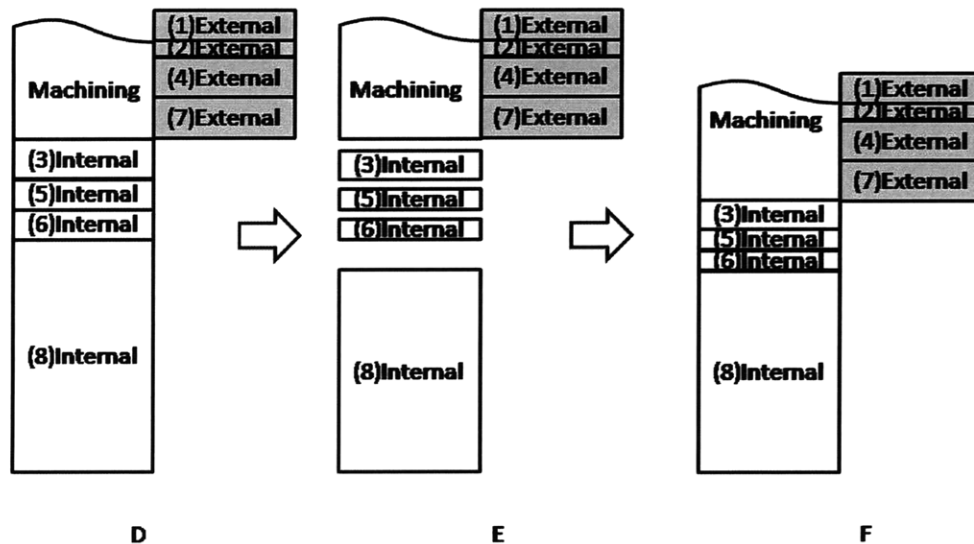
Figure 4-8 Setup operation simplification

In status E, all the internal operations need to be simplified in order to reduce individual operation time. After operation simplification, all operations are re-streamlined and the new setup operation sequence is formed in status F. Expectation for operation simplification is to reduce the individual operation time by 20%.

4.5.3 Operation simplification-Jaw change time reduction

In CNC machining, soft jaws usually made of aluminum are often custom cut or made to fit the part being held in the vise. Since they can be cut into fit the work piece, soft jaws are often used in place of fixtures or simple tooling. They are also used for rapid changeover type setups since they can be easily engraved with the part number, the job number, or other information relevant to the job being run. Soft jaws are considered "consumable" item. That is, they are discarded or recycled after multiple uses. On the other hand, hard jaws need no or less boring operation. For cells machining those parts with less finishing requirement, their jaws can be changed from soft jaws to hard jaws.

During each setup, the jaws need to be changed according to the diameter of the raw material. Three parts are involved in the jaw change: chuck, jaw holder and jaw. They are collected by bolts. Two dimension drawing about chuck configuration is shown in Figure 4-9.
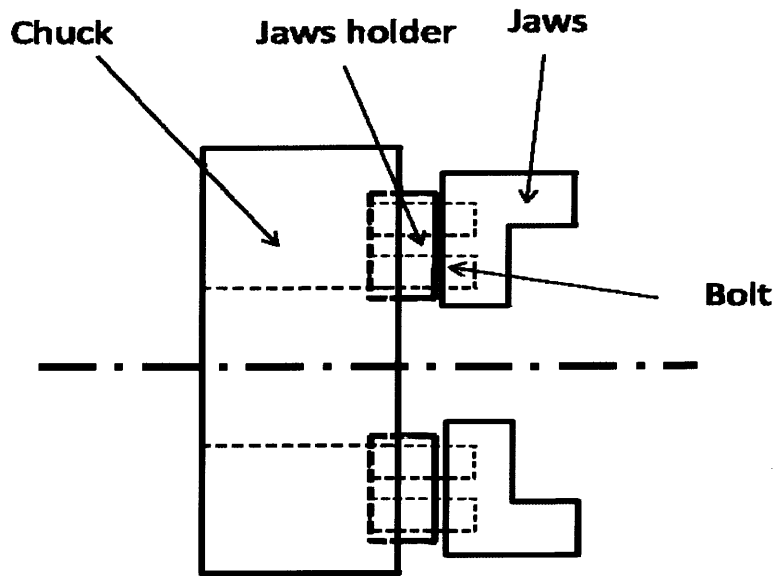
Figure 4-9 Chuck configuration

Before improvement, all sets of jaws share the same set of jaw holder. During jaw change,

the jaw change sequence is:
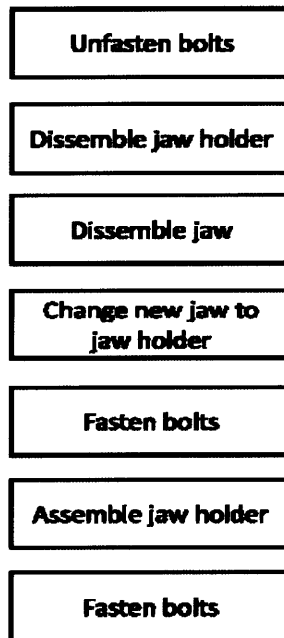
Figure 4-10 Jaw change sequence before improvement

The jaw change sequence before improvement is tedious and time-consuming. The project team sees the potential of removing some operations by consolidating the jaw to the jaw holder with bolts. In the jaw change sequence after improvement, jaw, jaw holder and bolts are consolidated as the jaw unit and the jaw change sequence is simplified as shown in Figure 4-11.

```
┌─────────────────────────┐
│     Unfasten bolts       │
└─────────────────────────┘

┌─────────────────────────┐
│    Dissemble jaw unit    │
└─────────────────────────┘

┌─────────────────────────┐
│   Change new jaw unit    │
└─────────────────────────┘

┌─────────────────────────┐
│      Fasten bolts        │
└─────────────────────────┘
```
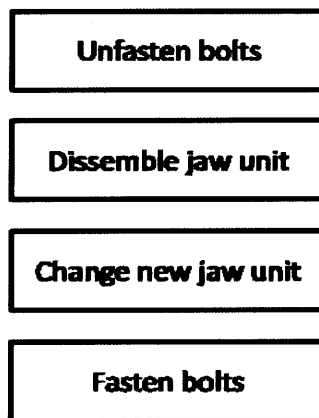
Figure 4-11 Jaw change sequence after improvement

For achieving the consolidation, new jaw holders and bolts are bought in to match each set of jaws.

4.5.4 Operation simplification- operator movements simplification

From Figure 4-12 in section 5.2, operators' movement during setup is complex. Some long distance movement requires a lot of time and more importantly, the operators' energy. One significant problem is that tooling areas are dispersed and some of them are quite far away from CNC machine which is the setup operation area. A cell rearrangement is highly required in order to simplify the movements. There are several actions to simplify the movements:

- Add one standby tool preparation area beside CNC machine so that the operator can get focused.

- Remove the far-away tooling area.

- Consolidate the dispersed tooling areas.

- Remove unnecessary operations during setup.

After improvement, a new spaghetti diagram can be generated to show the detailed movements. The benefit is obvious. Some long distance movement is eliminated and the total number of movements is reduced from 20 to 10. Most importantly, most of the movements in Figure 4-13 are congregated in a small area in front of CNC machine which is quite convenient for the operators.
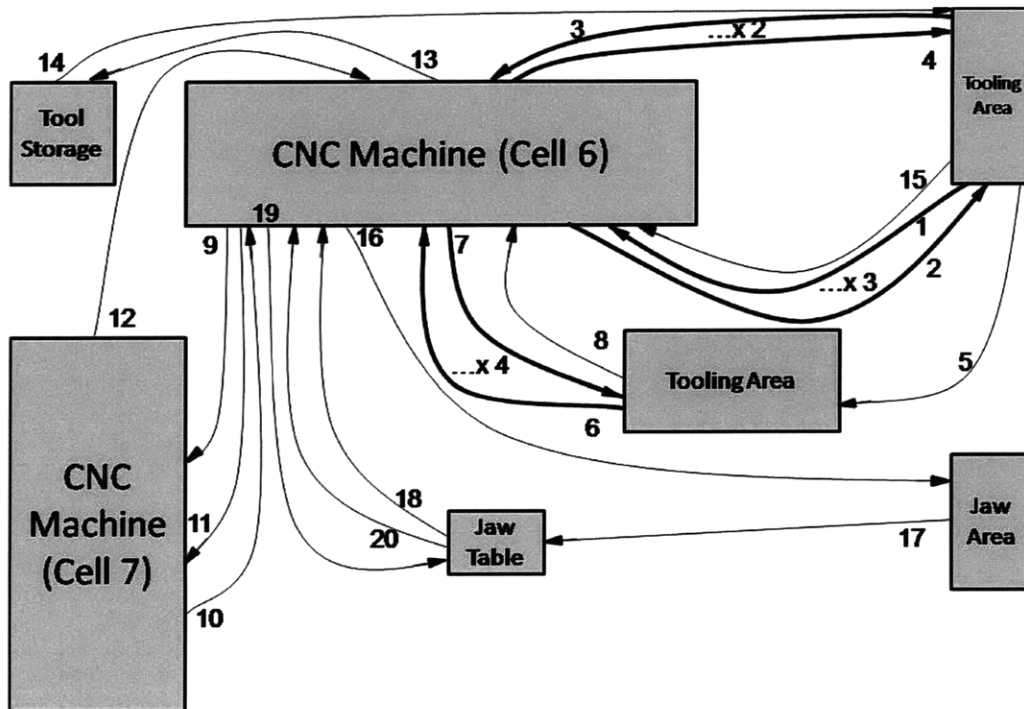
Figure 4-12 Spaghetti diagram for cell 6 before improvement

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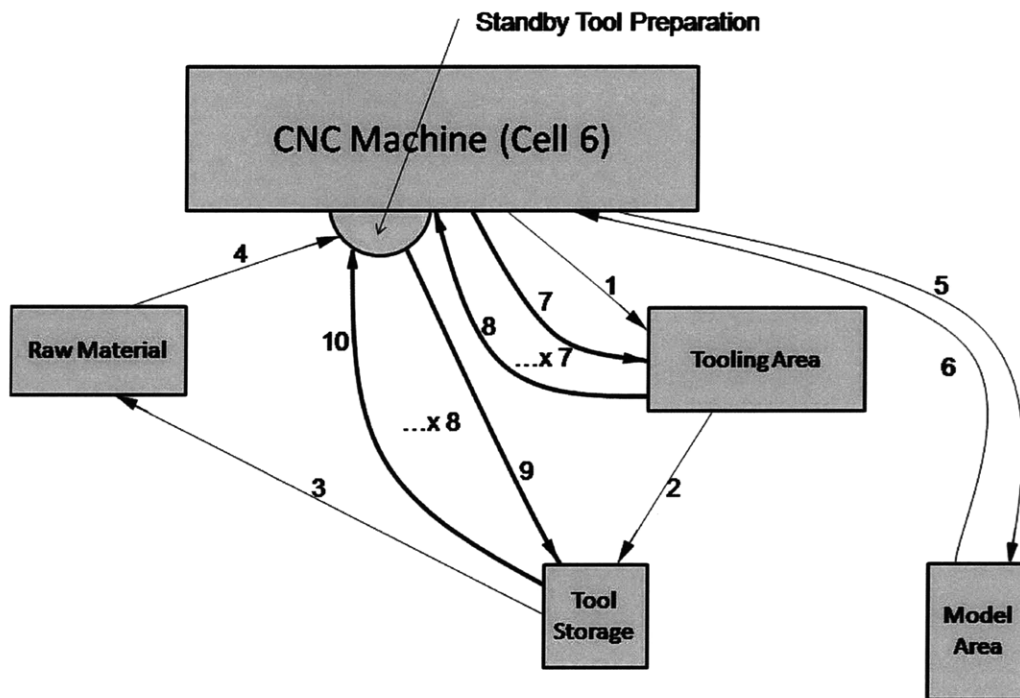
Figure 4-13 Spaghetti diagram for cell 6 after improvement

4.5.5 Operation simplification-other improvements

In addition to the major improvements illustrated in the previous sections, there are some other improvements which are not that significant but still need to be mentioned briefly. Disruption is frequent during setup. Cause and effect have been distinguished and designated solutions are pointed out respectively in the list below.

Disruptions' cause and effect list:

1. Mixed tools

2. Mixed holders and jaws

3. Mixed gauges

4. Frequent machine down

Designated solutions list:

1. Provide pre-kit tooling tray

2. Place tool holder & jaws near designated cell

3. Color measuring gauges

4. Enforce daily Preventive maintenance

Moreover, in order to reduce the setup time variance, the inexperienced operators need to be well trained and a standardized setup procedure is prepared for operators to follow. One thing needs to pointed out is that Chinese operators, some of whom cannot read English, is quite common phenomena. A Chinese version of setup procedure is necessary at this sense.

4.6 Summary

In general, the basic methodology of this project is implementing the Lean Manufacturing and SMED knowledge by observing wastes and eliminating wastes. Based on the data collection and data analysis in this chapter, all possible solutions are proposed in order to reduce the setup time. In section 4.5.1, manufacturing sequence is optimized to minimize the amount tools need to be changed. In section 4.5.2, by using SMED methodology, we category the setup steps and optimize the setup sequence so that some internal actions are converted into external actions. From section 4.5.3 to 4.5.5, detailed solutions are proposed to reduce the time in each step.

5 Results and Discussion

5.1 Introduction

This chapter will make an objective evaluation on the project results by calculating the setup time reduction and cost saving. Further discussion on these results will be performed at last.

5.2 Evaluation

5.2.1 Setup time analysis

Some of the improvement proposals have already been implemented a few months ago. Setup time during these months is recorded and statistical analysis is generated to see the difference from data before improvement. Details about the improvement statistical data are illustrated in Table 5-1.

Table 5-1 Improvement statistical data

Year	Item	Cell 5	Cell 6	Cell 7
2008	Average (hr)	2.99	3.75	4.12
	Standard Deviation	1.24	1.44	1.73
2009	Average (hr)	1.53	2.71	1.82
	Standard Deviation	0.53	1.22	0.92
Improvement (hr)		1.46	1.03	2.30
Improvement (%)		48.8%	27.6%	55.8%

Setup time for 2009 is only recorded for half a year because of time limitation. From the data above, the benefit is obvious and impressive. Both the average setup time and the standard deviation have been reduced significantly. Figure 5-1 gives a direct comparison between the average setup time in 2008 and in 2009.
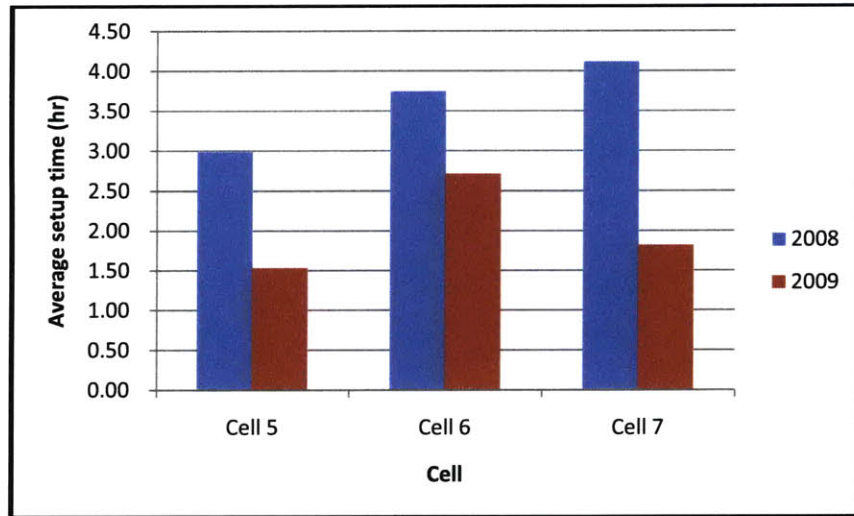
Figure 5-1 Average setup time comparison between 2008 and 2009

Table 5-2 Project wide improvement

Cell	5	6	7
Setup amount	170	177	199
Average setup time in 2008 (hr)	2.99	3.75	4.12
Average setup time in 2009 (hr)	1.53	2.71	1.82
Total setup time in 2008 (hr)	1990.77		
Total setup time in 2009 (hr)	1101.95		
Annual setup time reduction (hr)	888.82		
Improvement (%)	45%		

The project wide overall improvement is calculated in Table 5-2 to be 45%. Compared to the 30% improvement target proposed by managers at Schlumberger, this improvement is significant.

5.2.2 Cost saving analysis

This project will take setup time in 2008 as baseline and see the potential improvement in 2009. Since the setup in 2009 is not exactly the same with that in 2008, it is impossible to duplicate all the setups in 2008. This evaluation aims at figuring out for the same setup

amount as in 2008, how many hours can be reduced if setup were taken in the after-improvement situation.

For confidential reason, the exact labor rate in machining station in Schlumberger cannot be disclosed. In this thesis, the project team instead uses the average labor rate in Singapore (USD 15) and the average burden rate (USD 45)to calculate the expected cost saving. In each cell, the expected cost saving can be calculated as:

$$EC = (r_l + r_b) \times n_{2008} \times (t_{2008} - t_{2009})$$

EC _expected cost saving

r_l _labor rate

r_b _burden rate

n_{2008} _setup amount in 2008

t_{2008} _average setup time in 2008

t_{2009} _average setup time in 2009

Result for each cell is listed in Table 5-3.

Table 5-3 Expected cost saving

	Cell 5	Cell 6	Cell 7	Total
Amount of setup in 2008	170	177	199	
Average setup time in 2008 (hr)	2.99	3.75	4.12	
Average setup time in 2009 (hr)	1.53	2.71	1.82	
Total setup time reduction	248.2	184.08	457.7	
Expected annual cost saving	$ 14,892	$ 11,045	$ 27,462	$ 53,399

The economic situation in 2009 also affects the benefit by the improvement. In 2009, the economic depression has made the customer order amount shrunk to some extent and thus the setup amount in 2009 is also affected.

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5.3 Discussion

Cell 6 and cell 7 are similar since they both have two chucks which determine the setup procedure and setup workload is almost the same. It is expected that their setup time before improvement should be similar. However, by checking the historical data, cell 6 has both the less average setup time and the less standard deviation. It is analyzed to have two main reasons: the CNC machine in cell 6 is more accurate than that in cell 7; operators in cell 6 are more experienced.

However, this advantage also brings out the side effect. Even thought the total improvement (45%) exceeds the improvement target (30%), detailed improvement in cell 6 cannot meet demands. One reason behind this that the CNC machine in cell 6 is relatively more advanced. Especially for the internal tool eye sensor inside the CNC machine, its accuracy is much better than those of the other cells so that operator can be much more confident on the tool offset and thus control the machining process in a faster and better way. This advantage leaves us less space to improve.

The other reason is that the operator in cell 6 is more experienced and thus reluctant to change. When implementing the proposed solutions, especially for the operation sequence different from their habit, operators are more inclined to follow their own sequence, more or less.

5.4 Summary

In this chapter, we make a brief evaluation about the whole project regarding the time reduction and cost saving.   At last, we make a brief discussion on the results.

6 Future work

Currently, not all of the proposed solutions are implemented by the company. Solutions involving high investment in new machines or tools, such as external tooling measuring equipment, electronic or gas tools, are suspended and waiting for more proof and further discussion. In the near future, return on investment (ROI) analysis will be developed for these suspended proposals to see if it is profitable to bring in new machines or new tools.

By rechecking the operation elements in Table 5-4, operation 8 that consumes the most time has barely been addressed, largely because of technology limitation. Operation 8 comprises normal machining, inspection and rework, in which the normal machining time cannot be reduced because it directly affects the surface finishing of the parts. Frequent inspection and rework is necessary to compensate the inaccuracy in tooling offset sensor. In cell 5, 6, 7, most of the CNC machines have been used for more than 10 years so that inaccurate tooling offset sensor is understandable. Figuring out a way to remove that time or reduce that time to an acceptable level without bringing in high cost is exigently needed by the company in order to reduce the setup time. Moreover, this future work will involve the cooperation with CNC machine experts and frequent testing and experiment, which will require the machines to be shut down during project. This will further challenge the limited capacity in H&B manufacturing.

After summarizing a systematic way of doing improvements toward the setup reduction by taking trial on cell 5, 6 and 7, other cells will also implement these improvements in the future.

7 Project-wide conclusion and recommendation

According to the data record, one major problem in head and base manufacturing is the frequent setup and long setup time. After analyzing the data, this report has outlined the SMED methods to reduce the CNC machine setup time for cell 5, 6 and 7, all of which are used to manufacturing H&B parts.

Manufacturing sequence is first optimized to minimize the amount of tools needed to be changed and thus reduce the setup time. After that, the setup procedures are categorized into basic elements and an optimum setup sequence is developed to convert some internal actions to external actions. Solutions aiming at reducing the time in each individual setup element are proposed later on. Details about all the solutions are summarized in Table 7-1. According to the cause and effect classification in data analysis (Figure 4-6), designated solutions are classified and listed in Table 7-1.

Table 7-1 Solution summary

Improvements	Category
1st step	
Optimize manufacturing sequence	Method
2nd step	
Optimize setup sequence	Method
3rd step	
Simplify operator movements	Environment
Change soft jaw to hard jaw	Method
Consolidate jaw with jaw holder	Method
Use electronic or gas tooling	Method
Use external tooling measurement	Machine
Use pre-kit tooling tray	Method
Place tool holder and jaw near designated cell	Environment
Color coded measuring gauges	Method
Daily preventive maintenance	Machine
Standardize worksheet	People

Evaluations are made regarding how much time is reduced. After all possible solutions

are analyzed, the expected setup time reduction is 45%. However, because some of the

proposals have not been implemented, the actual setup time reduction improvement

shrinks. Setup time in cell 5 is reduced by 48.8% while cell 6 by 27.6% and cell 7 by

55.8%. This achievement, even though shrunk by the partial implementation of proposals,

is significant and impressive. On the other hand, the cost saving which is affected by the

economic depression in 2009 arrives 53,000 USD.

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APPENDIX A: Value stream map (VSM) before improvement

Value stream map (VSM) before improvement showing process flow from Supplier through Sawing, Machining, Warehouse receive, Warehouse issue, Subassembly, Warehouse receive, Warehouse issue to Customer, with Production control board, MRP, Monthly forecast, Information, and Weekly Schedule.

Process	Sawing	Machining	Warehouse receive	Warehouse issue	Subassembly	Warehouse receive	Warehouse issue
Data	C/T=7 mins 3 shifts C/O=5 mins Uptime=95% Avai.=63% Op.=1	C/T=60 mins 3 shifts C/O=180 mins Uptime=90% Avai.=63% Op.=8	C/T=30 mins NVA=10 mins 1 shift Avai.=95% Op.=2	C/T=40 mins NVA=20 mins 1 shift Avai.=95% Op.=2	C/T=20 mins 3 shifts Op.=2	C/T=30 mins NVA=15 mins 1 shift Avai.=95% Op.=2	C/T=30 mins NVA=15 mins 1 shift Avai.=95% Op.=1

Inventory triangles: 12 hrs, 9 days, 7 days, 1 days, 10 days

Timeline: 7 min | 60 min | 720 min | 30 min | 11340 min | 40 min | 8820 min | 20 min | 1260 min | 30 min | 12600 | 30 min

Lead Time: 34853 min

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APPENDIX B: VB code for matrix generation

```
Sub Matrix()
    Sheets("Sheet3").Select
    Tool1 = 2
    Tool2 = 2
    row = 2
    Dim number As Integer
    Dim i As Integer
    Dim time As Double
    number = 1
    time = Sheets("Sheet3").Cells(Tool1 + 19, Tool2)
    For i = 2 To 256
        If Cells(1, i) <> "" Then
        number = number + 1
        End If
    Next i
    Cells(14, 2).Value = number - 1
    For Tool1 = 2 To number
        For Tool2 = 2 To number
            time = 0
            For row = 2 To 13
                If Cells(row, Tool1) = Cells(row, Tool2) Then
                    time = time
                Else If Cells(row, Tool1) <> "" Then
                    If Cells(row, Tool2) = "" Then
                    time = time + Cells(18, 2)
                    Else
                    time = time + Cells(16, 2)
                    End If
                Else
                    time = time + Cells(17, 2)
                End If
            Next row
            Cells(Tool1 + 19, Tool2).Value = time
        Next Tool2
    Next Tool1
End Sub
```

APPENDIX C: VB code for sequence optimization

```
Sub optimization()
Sheets("Sheet1").Select
Dim time As Double
Dim time0 As Double
Dim number As Integer
Dim i As Integer
i = 0
number = 0
Sheet1.Range("A13:H13") = ""
Sheet2.Range("A1:H5040") = ""
For j = 2 To 8
    If Cells(1, j) <> "" Then
    number = number + 1
    End If
Next j
Select Case number
    Case 3
        Cells(17, 1).Value = Cells(2, 3).Value + Cells(3, 4).Value
        For a = 2 To 4
            For b = 2 To 4
                For c = 2 To 4
                    If (b <> a) And (c <> a) And (c <> b) Then
                        time = Cells(a, b).Value + Cells(b, c).Value
                        Sheet2.Cells(1 + i, 1).Value = time
                        Sheet2.Cells(1 + i, 2) = Sheet1.Cells(a, 1)
                        Sheet2.Cells(1 + i, 3) = Sheet1.Cells(b, 1)
                        Sheet2.Cells(1 + i, 4) = Sheet1.Cells(c, 1)
                        i = i + 1
                    End If
                Next c
            Next b
        Next a
        Sheet1.Cells(13, 1) = Sheet2.Cells(1, 1)
        Sheet1.Cells(13, 2) = Sheet2.Cells(1, 2)
        Sheet1.Cells(13, 3) = Sheet2.Cells(1, 3)
        Sheet1.Cells(13, 4) = Sheet2.Cells(1, 4)
        For N = 1 To 6
            If Sheet2.Cells(N, 1) < Sheet1.Cells(13, 1) Then
                Sheet1.Cells(13, 1) = Sheet2.Cells(N, 1)
                Sheet1.Cells(13, 2) = Sheet2.Cells(N, 2)
                Sheet1.Cells(13, 3) = Sheet2.Cells(N, 3)
                Sheet1.Cells(13, 4) = Sheet2.Cells(N, 4)
            End If
        Next N
    Case 4
        Cells(17, 1).Value = Cells(2, 3).Value + Cells(3, 4).Value + Cells(4, 5).Value
        For a = 2 To 5
            For b = 2 To 5
                For c = 2 To 5
                    For d = 2 To 5
```

```
                                        If (b <> a) And (c <> a) And (c <> b) And (d <> a) And (d <> b) And (d
<> c) Then
                                        time = Cells(a, b).Value + Cells(b, c).Value + Cells(c, d).Value
                                        Sheet2.Cells(1 + i, 1).Value = time
                                        Sheet2.Cells(1 + i, 2) = Sheet1.Cells(a, 1)
                                        Sheet2.Cells(1 + i, 3) = Sheet1.Cells(b, 1)
                                        Sheet2.Cells(1 + i, 4) = Sheet1.Cells(c, 1)
                                        Sheet2.Cells(1 + i, 5) = Sheet1.Cells(d, 1)
                                        i = i + 1
                                End If
                        Next d
                    Next c
                Next b
            Next a
            Sheet1.Cells(13, 1) = Sheet2.Cells(1, 1)
            Sheet1.Cells(13, 2) = Sheet2.Cells(1, 2)
            Sheet1.Cells(13, 3) = Sheet2.Cells(1, 3)
            Sheet1.Cells(13, 4) = Sheet2.Cells(1, 4)
            Sheet1.Cells(13, 5) = Sheet2.Cells(1, 5)
            For N = 1 To 24
                If Sheet2.Cells(N, 1) < Sheet1.Cells(13, 1) Then
                    Sheet1.Cells(13, 1) = Sheet2.Cells(N, 1)
                    Sheet1.Cells(13, 2) = Sheet2.Cells(N, 2)
                    Sheet1.Cells(13, 3) = Sheet2.Cells(N, 3)
                    Sheet1.Cells(13, 4) = Sheet2.Cells(N, 4)
                    Sheet1.Cells(13, 5) = Sheet2.Cells(N, 5)
                End If
            Next N
        Case 5
            Cells(17, 1).Value = Cells(2, 3).Value + Cells(3, 4).Value + Cells(4, 5).Value + Cells(5,
6).Value
            For a = 2 To 6
                For b = 2 To 6
                    For c = 2 To 6
                        For d = 2 To 6
                            For e = 2 To 6
                                If (b <> a) And (c <> a) And (c <> b) And (d <> a) And (d <> b)
And (d <> c) And (e <> a) And (e <> b) And (e <> c) And (e <> d) Then
                                    time = Cells(a, b).Value + Cells(b, c).Value + Cells(c,
d).Value + Cells(d, e).Value
                                    Sheet2.Cells(1 + i, 1).Value = time
                                    Sheet2.Cells(1 + i, 2) = Sheet1.Cells(a, 1)
                                    Sheet2.Cells(1 + i, 3) = Sheet1.Cells(b, 1)
                                    Sheet2.Cells(1 + i, 4) = Sheet1.Cells(c, 1)
                                    Sheet2.Cells(1 + i, 5) = Sheet1.Cells(d, 1)
                                    Sheet2.Cells(1 + i, 6) = Sheet1.Cells(e, 1)
                                    i = i + 1
                                End If
                            Next e
                        Next d
                    Next c
                Next b
            Next a
```

```
Sheet1.Cells(13, 1) = Sheet2.Cells(1, 1)
Sheet1.Cells(13, 2) = Sheet2.Cells(1, 2)
Sheet1.Cells(13, 3) = Sheet2.Cells(1, 3)
Sheet1.Cells(13, 4) = Sheet2.Cells(1, 4)
Sheet1.Cells(13, 5) = Sheet2.Cells(1, 5)
Sheet1.Cells(13, 6) = Sheet2.Cells(1, 6)
For N = 1 To 120
      If Sheet2.Cells(N, 1) < Sheet1.Cells(13, 1) Then
            Sheet1.Cells(13, 1) = Sheet2.Cells(N, 1)
            Sheet1.Cells(13, 2) = Sheet2.Cells(N, 2)
            Sheet1.Cells(13, 3) = Sheet2.Cells(N, 3)
            Sheet1.Cells(13, 4) = Sheet2.Cells(N, 4)
            Sheet1.Cells(13, 5) = Sheet2.Cells(N, 5)
            Sheet1.Cells(13, 6) = Sheet2.Cells(N, 6)
      End If
   Next N
Case 6
      Cells(17, 1).Value = Cells(2, 3).Value + Cells(3, 4).Value + Cells(4, 5).Value + Cells(5,
6).Value + Cells(6, 7).Value
      For a = 2 To 7
            For b = 2 To 7
                  For c = 2 To 7
                        For d = 2 To 7
                              For e = 2 To 7
                                    For f = 2 To 7
                                          If (b <> a) And (c <> a) And (c <> b) And (d <> a) And (d <>
b) And (d <> c) And (e <> a) And (e <> b) And (e <> c) And (e <> d) And (f <> a) And (f <> b) And
(f <> c) And (f <> d) And (f <> e) Then
                                                time = Cells(a, b).Value + Cells(b, c).Value + Cells(c,
d).Value + Cells(d, e).Value + Cells(e, f).Value
                                                Sheet2.Cells(1 + i, 1).Value = time
                                                Sheet2.Cells(1 + i, 2) = Sheet1.Cells(a, 1)
                                                Sheet2.Cells(1 + i, 3) = Sheet1.Cells(b, 1)
                                                Sheet2.Cells(1 + i, 4) = Sheet1.Cells(c, 1)
                                                Sheet2.Cells(1 + i, 5) = Sheet1.Cells(d, 1)
                                                Sheet2.Cells(1 + i, 6) = Sheet1.Cells(e, 1)
                                                Sheet2.Cells(1 + i, 7) = Sheet1.Cells(f, 1)
                                                i = i + 1
                                          End If
                                    Next f
                              Next e
                        Next d
                  Next c
            Next b
      Next a
      Sheet1.Cells(13, 1) = Sheet2.Cells(1, 1)
      Sheet1.Cells(13, 2) = Sheet2.Cells(1, 2)
      Sheet1.Cells(13, 3) = Sheet2.Cells(1, 3)
      Sheet1.Cells(13, 4) = Sheet2.Cells(1, 4)
      Sheet1.Cells(13, 5) = Sheet2.Cells(1, 5)
      Sheet1.Cells(13, 6) = Sheet2.Cells(1, 6)
      Sheet1.Cells(13, 7) = Sheet2.Cells(1, 7)
      For N = 1 To 720
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            If Sheet2.Cells(N, 1) < Sheet1.Cells(13, 1) Then
                Sheet1.Cells(13, 1) = Sheet2.Cells(N, 1)
                Sheet1.Cells(13, 2) = Sheet2.Cells(N, 2)
                Sheet1.Cells(13, 3) = Sheet2.Cells(N, 3)
                Sheet1.Cells(13, 4) = Sheet2.Cells(N, 4)
                Sheet1.Cells(13, 5) = Sheet2.Cells(N, 5)
                Sheet1.Cells(13, 6) = Sheet2.Cells(N, 6)
                Sheet1.Cells(13, 7) = Sheet2.Cells(N, 7)
            End If
        Next N
    Case 7
        Cells(17, 1).Value = Cells(2, 3).Value + Cells(3, 4).Value + Cells(4, 5).Value + Cells(5,
6).Value + Cells(6, 7).Value + Cells(7, 8).Value
        For a = 2 To 8
            For b = 2 To 8
                For c = 2 To 8
                    For d = 2 To 8
                        For e = 2 To 8
                            For f = 2 To 8
                            For g = 2 To 8
                                If (b <> a) And (c <> a) And (c <> b) And (d <> a) And (d <>
b) And (d <> c) And (e <> a) And (e <> b) And (e <> c) And (e <> d) And (f <> a) And (f <> b) And
(f <> c) And (f <> d) And (f <> e) And (g <> a) And (g <> b) And (g <> c) And (g <> d) And (g <> e)
And (g <> f) Then
                                    time = Cells(a, b).Value + Cells(b, c).Value + Cells(c,
d).Value + Cells(d, e).Value + Cells(e, f).Value + Cells(f, g).Value
                                    Sheet2.Cells(1 + i, 1).Value = time
                                    Sheet2.Cells(1 + i, 2) = Sheet1.Cells(a, 1)
                                    Sheet2.Cells(1 + i, 3) = Sheet1.Cells(b, 1)
                                    Sheet2.Cells(1 + i, 4) = Sheet1.Cells(c, 1)
                                    Sheet2.Cells(1 + i, 5) = Sheet1.Cells(d, 1)
                                    Sheet2.Cells(1 + i, 6) = Sheet1.Cells(e, 1)
                                    Sheet2.Cells(1 + i, 7) = Sheet1.Cells(f, 1)
                                    Sheet2.Cells(1 + i, 8) = Sheet1.Cells(g, 1)
                                    i = i + 1
                                End If
                            Next g
                            Next f
                        Next e
                    Next d
                Next c
            Next b
        Next a
        Sheet1.Cells(13, 1) = Sheet2.Cells(1, 1)
        Sheet1.Cells(13, 2) = Sheet2.Cells(1, 2)
        Sheet1.Cells(13, 3) = Sheet2.Cells(1, 3)
        Sheet1.Cells(13, 4) = Sheet2.Cells(1, 4)
        Sheet1.Cells(13, 5) = Sheet2.Cells(1, 5)
        Sheet1.Cells(13, 6) = Sheet2.Cells(1, 6)
        Sheet1.Cells(13, 7) = Sheet2.Cells(1, 7)
        Sheet1.Cells(13, 8) = Sheet2.Cells(1, 8)
        For N = 1 To 5040
            If Sheet2.Cells(N, 1) < Sheet1.Cells(13, 1) Then
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                    Sheet1.Cells(13, 1) = Sheet2.Cells(N, 1)
                    Sheet1.Cells(13, 2) = Sheet2.Cells(N, 2)
                    Sheet1.Cells(13, 3) = Sheet2.Cells(N, 3)
                    Sheet1.Cells(13, 4) = Sheet2.Cells(N, 4)
                    Sheet1.Cells(13, 5) = Sheet2.Cells(N, 5)
                    Sheet1.Cells(13, 6) = Sheet2.Cells(N, 6)
                    Sheet1.Cells(13, 7) = Sheet2.Cells(N, 7)
                    Sheet1.Cells(13, 8) = Sheet2.Cells(N, 8)
            End If
        Next N
    Case Is <= 2
        MsgBox "The minimum No. of parts to be optimized is 3!"
    Case Else
        MsgBox "The maximum No. of parts can be optimized is 7!"
End Select
End Sub
```