Manpower Planning and Cycle-Time Reduction of a Labor-Intensive Assembly Line

By

Shao Chong Oh

B.Eng. Mechanical Engineering (Mechatronics) 2009
Nanyang Technological University, Singapore

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Signature of Author: ______________________________
Department of Mechanical Engineering
August 6, 2010

Certified by: ______________________________
Stephen C. Graves
Abraham J. Siegel Professor of Management Science
Department of Mechanical Engineering and Engineering Systems
Thesis Supervisor

Accepted by: ______________________________
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Committee on Graduate Students

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Abstract

The demand for Gas Lift Mandrels(GLM) in the oil and gas industry is expected to increase over the next few years, requiring Schlumberger's GLM assembly line to increase their manufacturing capacity. Given the labor-intensive nature of Schlumberger's GLM assembly line, other than implementing kaizens and purchasing more equipment, it is important to also consider manpower issues. This research analyzes manpower management issues in the GLM assembly line to meet the projected increase in customer demand over the next three years.

A detailed time study was conducted to understand and characterize all processes in the assembly line, before manpower plans were drawn up for each year till 2013. Several manpower scheduling concepts were incorporated in the manpower plan, such as Job Rotation and Workforce Flexibility to optimize the rate of utilization, human performance and well-being. By clustering processes together, the labor utilization rate can be increased to more than ninety percent. A new position of grinders has also been proposed to assist in various grinding operations, in order to reduce the cycle times of processes, to help workers gain better focus in their work and to reduce the cost of labor.

Disclaimer: All numerical data and results presented have been manipulated to protect the confidentiality of the company.

Keywords:

Gas Lift Mandrels(GLM), workforce flexibility, manpower planning/scheduling

Thesis Supervisor: Stephen C. Graves

Title: Professor, Department of Mechanical Engineering

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1 Introduction

1.1 Company Background

Schlumberger Limited is a world-leading multi-national oilfield services company that employs over 83,000 people in 80 countries[1]. The company provides the technology, information solutions, and integrated project management services to its customers in the oil and gas industry through two business segments:

- **Schlumberger Oilfield Services** offers a wide variety of products and services in formation evaluation, well construction and completions, equipment for oil production, consulting, and IT management services in support of their clients' operations.
- **WesternGeco** is the world's largest seismic company which provides advanced acquisition and data processing services.

The Singapore Integration Center (SPE) is Schlumberger Oilfield Services' biggest Engineering, Manufacturing and Sustaining facility for Artificial Lift products. The plant is equipped with a foundry, machine shops, assembly shops, a heat treatment furnace and a comprehensive set of Quality Control testing facilities.

Products that are manufactured in SPE include Gas Lift Valves (GLVs), bypasses, temperature/pressure gauges, components and subassemblies for the Electric Submersible Pumps (ESPs), and Gas Lift Mandrels (GLMs). These Artificial Lift products are used in oil wells that have no natural flow due to insufficient reservoir pressure. ESPs are motor-driven pumps that are used to extract crude oil from the wells, while GLMs infuse gas bubbles into the crude oil, reducing its density and enabling it to float to the surface.

1.2 Product Description

GLMs are preferred in oil wells with a corrosive nature, such as those with higher acidity or sand composition, as GLMs have fewer mechanical parts that will be subject to considerable wear and tear during operation. As mentioned in the previous section, after the mandrel is lowered into the oil well, a small amount of compressed gas is injected into the oil-filled mandrel to aerate the fluid, reducing its density and causing the oil to be lifted out of the oil well. Figure 1-1 below illustrates the working of such a mandrel.

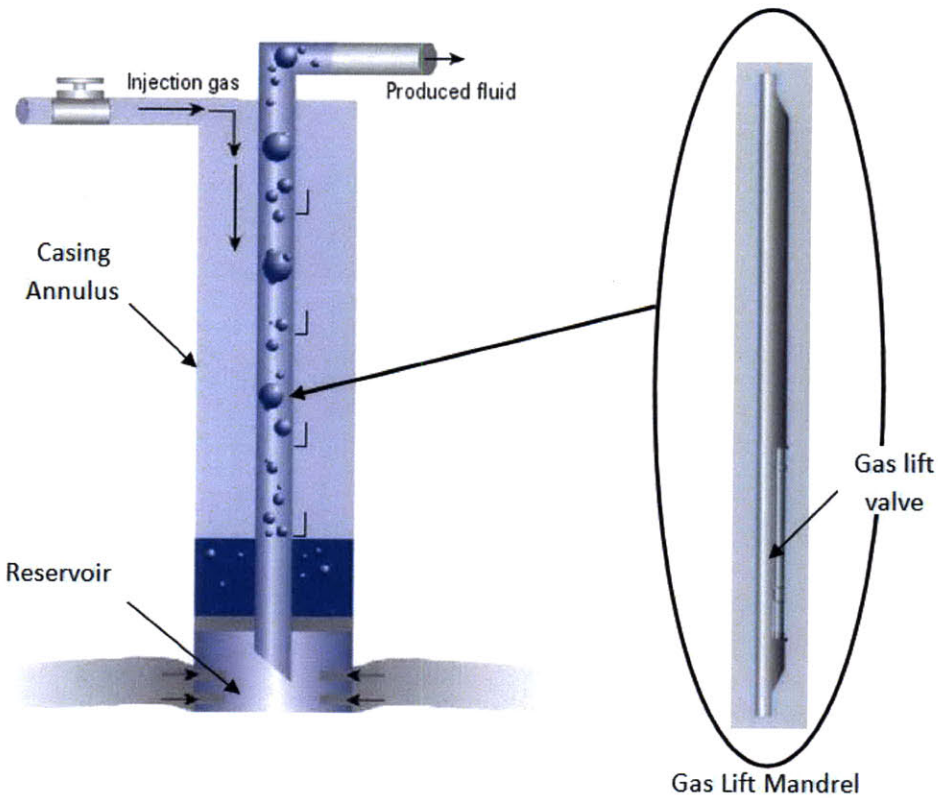

Figure 1-1: A Gas Lift Mandrel (GLM) in operation[1]

GLMs are manufactured in different diameters, lengths, features, and materials, and can be categorized into various product families accordingly. However, significant manufacturing differences only occur between two groups of mandrels; mandrels that have round cross-sections, and mandrels that have oval cross-sections. On average, the mandrels are approximately two metres in length, and twenty centimeters in diameter.

Round mandrels can be further broken down into two types; standard round mandrels and long round mandrels. Standard round mandrels are made up of six components, while long round mandrels are made up of four components. These components are shown in Figure 1-2 and Figure 1-3 for both types of round mandrels respectively.

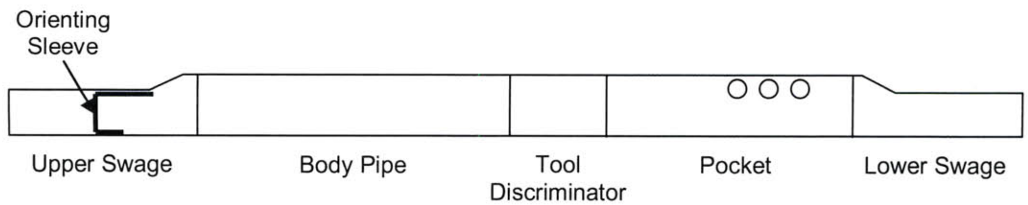

Figure 1-2: Components of standard round mandrels

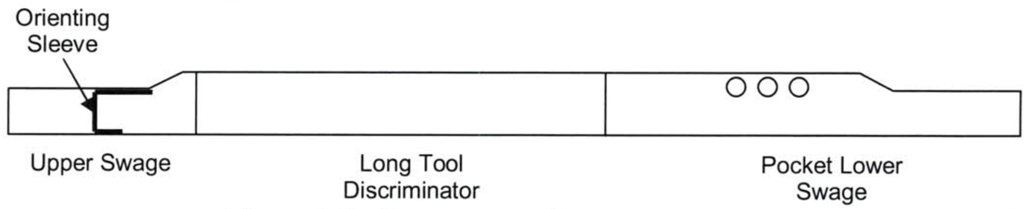

Figure 1-3: Components of long round mandrels

Oval mandrels, on the other hand, consist of four slightly-different main components, as illustrated in Figure 1-4 below.

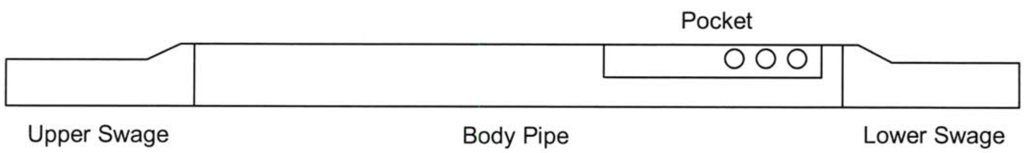

Figure 1-4: Components of an oval mandrel

1.3 Gas Lift Mandrel Manufacturing Process

The general manufacturing process flow for oval and round mandrels is shown in Figure 1-5 below.

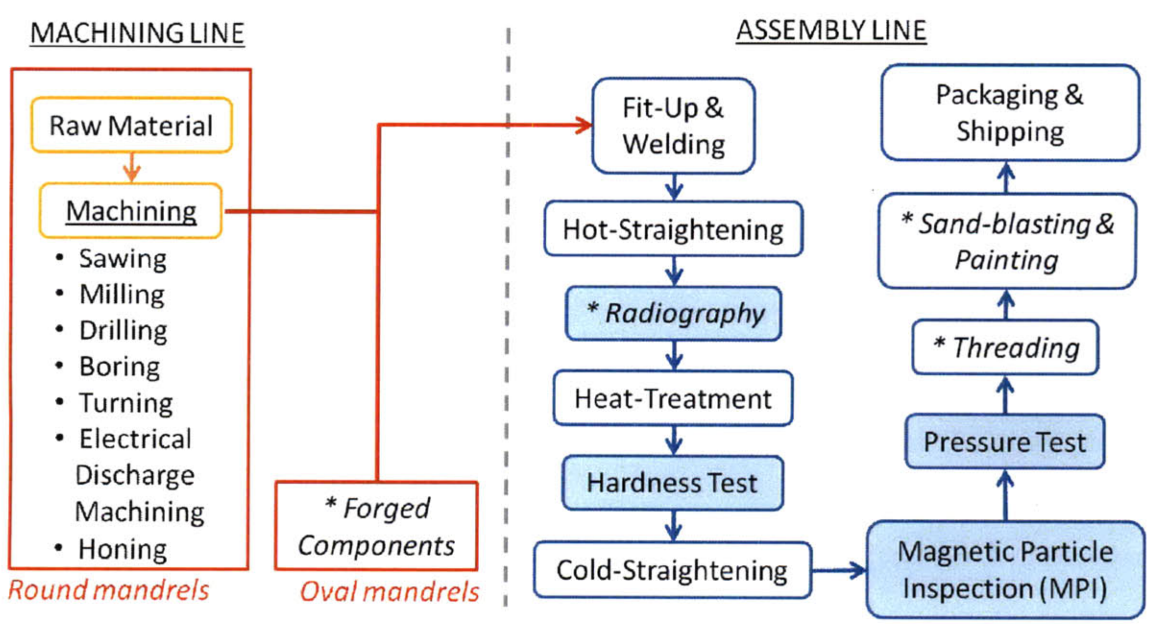

Figure 1-5: General process flow chart of GLM production line for oval and round mandrels

The overall manufacturing process can be separated into the machining and assembly lines. As shown in Figure 1-5 above, four components of the oval mandrels are forged by an outsourced supplier and need not go through the in-house machining line. These forged components go directly into the assembly line which starts with the Fit-Up process and ends with Packaging and Shipping. The four or six components of round mandrels, on the other hand, are firstly machined in-house from raw bar-stock purchased from an external supplier before proceeding downstream into the assembly line. All assembly workstations that the round and oval mandrels flow through are shared. Both types of mandrels have similar assembly processes and are treated equally.

There are four inspection processes in the assembly line that are highlighted in blue, namely Radiography, Hardness Test, Magnetic Particle Inspection (MPI), and Pressure Test. Processes in italic font are currently outsourced processes, namely Radiography, Threading, Sand-blasting, and Painting.

GLMs are highly customized in nature; whenever a customer places an order, a team of designers will discuss with the customer to understand his needs and to work out the mandrels' technical specifications. Depending on the customer's requirements, the mandrels may have unique features, or features with dimensions different from other mandrels. Thus, mandrel components of a particular customer's order will have their own unique part numbers as component identifiers. Multiple parts, each with a component part number, are then given a new serial number when they are assembled together to identify the particular mandrel. Figure 1-6 below illustrates this. The manufacturing process flow might differ slightly from time to time depending on specific customer requirements. Currently there are about 50 different designs of oval mandrels and about 40 different designs of round mandrels. Each time a new mandrel design with new features is released, new mandrel part numbers are created. A more detailed description and analysis of the process flow will be covered in Chapter 2.

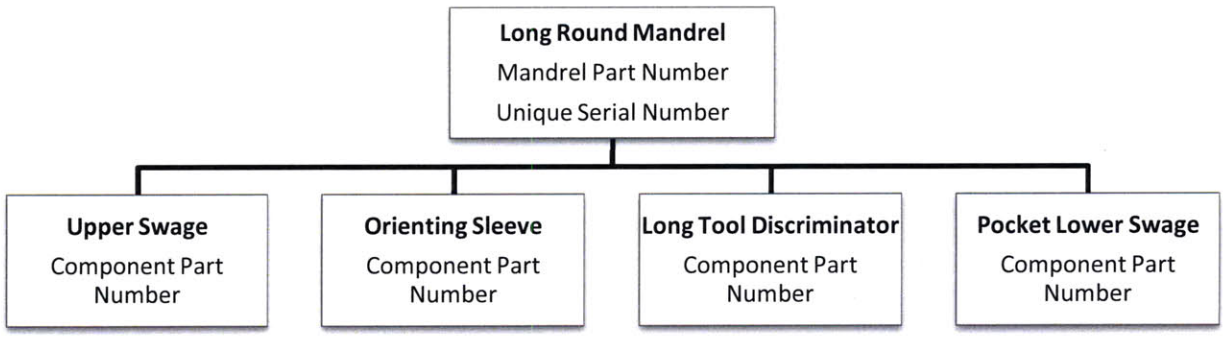

Figure 1-6: A long round mandrel that is made up of four components

1.4 Current Manufacturing Issues

Significant growth in the sales of Gas Lift mandrels is expected in the coming years. In order to make Schlumberger the one of the market leaders in Gas Lift systems worldwide, efforts to increase manufacturing capacity to meet customer demand with competitive lead time, cost, and quality have been put in place.

Table 1-1 below shows the projected number of mandrels that need to be produced per week over the next few years.

Table 1-1: Projected number of mandrels to be produced per week

Year	Oval mandrels per week	Round mandrels per week	Total mandrels per week
2009	13	3	**16**
2010	38	9	**47**
2011	60	25	**85**
2012	103	25	**128**
2013	120	26	**146**

The current manufacturing capacity is able to produce a maximum of 50 mandrels per week. Thus, it is necessary to improve the throughput rate in order to meet the projected demand over the next few years. Capacity expansion projects might become a need should the above trend in future demand materialize.

Also, current manufacturing lead times are much longer than total processing times due to excessive Work-In-Process (WIP). This results in high non-value-adding (waiting) times. We note that achieving less WIP will reduce waiting times and consequently reduce the manufacturing lead times. Shorter manufacturing lead times will in turn enable a quicker response to customer orders, ensuring better customer service and on-time delivery.

The above issues have various contributing factors. One of them is the unbalanced manpower distribution among workstations in the assembly line, which will be discussed in more detail in Chapter 2. Engineers and managers in the department are aware of this problem and have been trying to find a solution to it. This project seeks to address this problem, and further discussion will follow in the other sections of this thesis.

2 Problem Statement

2.1 Introduction

The focus of this project is to address manpower management issues in the GLM assembly line to meet the expected increase in customer demand over the next three years. This chapter describes the problem to be addressed in greater detail by characterizing the GLM assembly line.

2.2 The Process Flow

As introduced in Section 1.3, the components for both round and oval mandrels arrive at the first station of the assembly line as separate pieces upon the release of a Work Order by the Production Planner. A Work Order of round mandrels typically consists of a batch of four mandrels, while that of oval mandrels contains four to six mandrels. Work Orders are sized this way so that one Work Order of mandrels can fit into the heat treatment furnace as a batch. Oval mandrels are generally smaller than their round counterparts, thus their Work Orders can be slightly larger.

Both round and oval mandrels go through similar assembly processes, sharing many other resources along the line. This can be seen in Figure 2-1 and Figure 2-2. After the components are tack welded together at their respective fit up stations, they go through the same assembly and inspection stations in the shop floor. However, due to differences in material, size and features of the two types of mandrels, there are several differences in the assembly process:

1. Processing times of round mandrels may be longer or shorter than oval mandrels. For example, as round mandrels do not go through plasma cutting and welding of pockets, they warp less and thus pass through the Hot Straightening station faster. However, at round mandrels tend to stay longer in the OD grinding machine as they are bigger and made of harder materials.
2. Round and oval mandrels have different Non-Destructive Examination (NDE) standards, imposing different requirements on them. Some materials or types of mandrels may require only partial sampling to be performed at the inspection processes, while some may need 100% inspection.
3. Some round mandrels have special features which require additional processing, such as guard rails or keeper plates. Oval mandrels do not enter any of these additional processes.

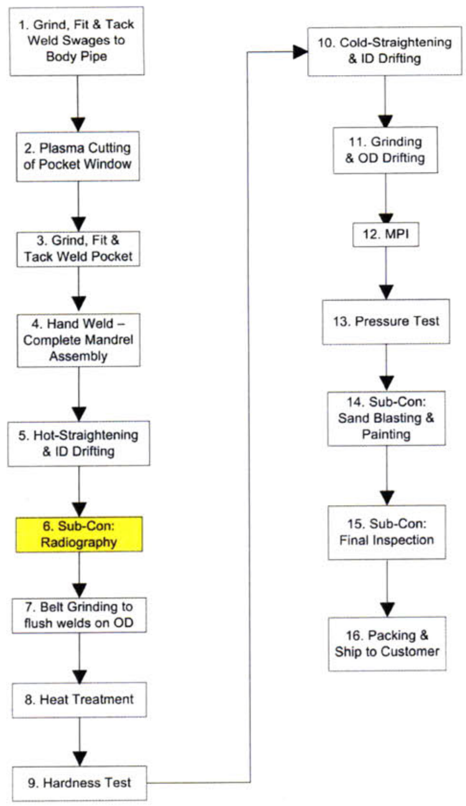

Figure 2-1: Process flow of oval mandrels[2]

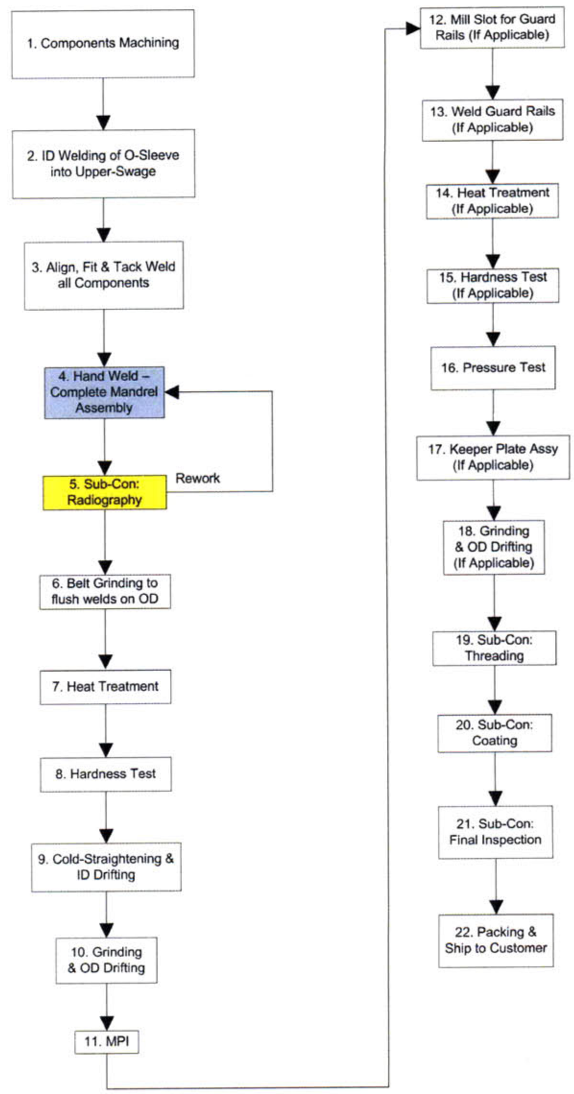

Figure 2-2: Process flow of round mandrels

2.3 Characterization of the Assembly Line

A tour of the assembly line will reveal that all processes are very labor-dependent, except for the robotic plasma cutter and heat treatment furnace, both of which only require a worker for loading and unloading mandrels. All other processes require at least one worker to be present for each mandrel in process. For example, at a full welding booth, the welder will push a tack-welded mandrel into the booth, grind off the tack-welds and perform a full welding procedure manually. A characteristic of such a labor-intensive process is that the processing time will be highly variable. A refreshed and alert worker will be able to weld faster than one who is physically ill or exhausted. In addition, an experienced welder will be able to work faster than a newly trained welder. This makes it difficult to determine a single, representative processing time for each of the processes.

As welding is the only procedure used to join the components together to form a mandrel, the quality of welds is critical to the overall functionality of the mandrel. Porosities in the weld may cause leakages to occur when the mandrel is in operation. In extreme but possible scenarios, the mandrels may explode at the welds when subject to high pressures. This is the reason why quality inspections in the assembly line are so important, especially the pressure test bay which is termed as a functionality test. Figure 2-3 shows the First Pass Yield percentage of mandrels that are tested in each of the inspection stations, from January 2009 to April 2010.

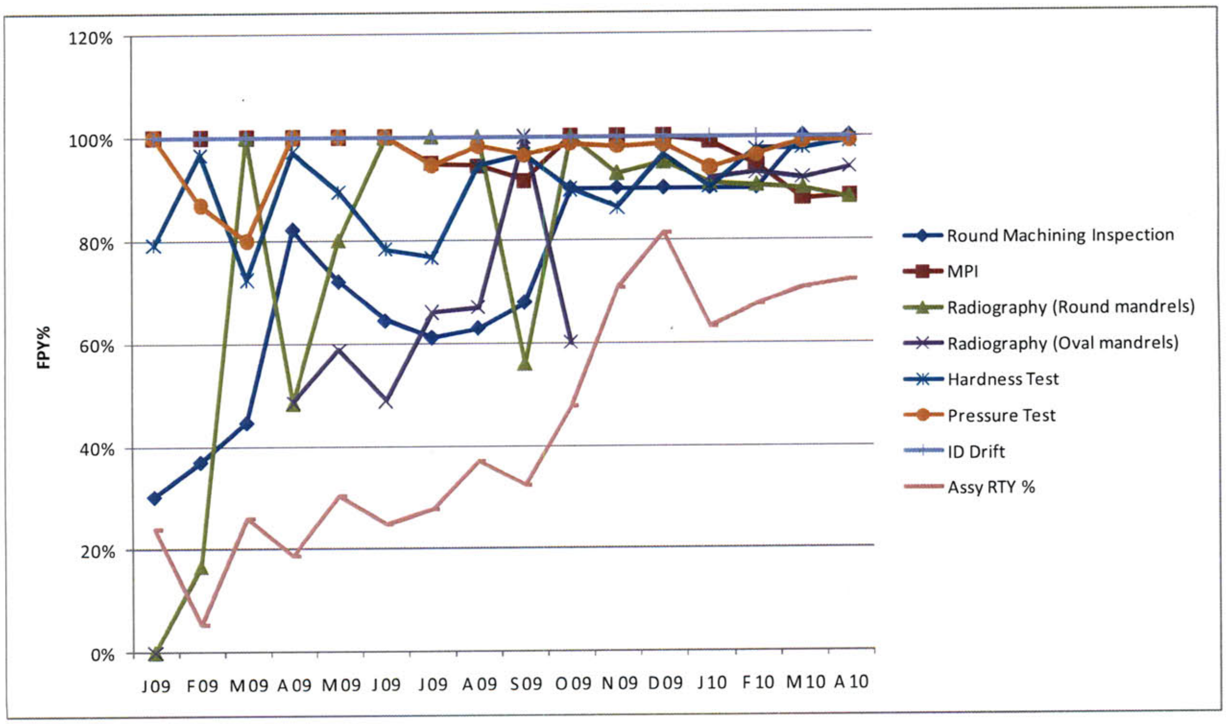

Figure 2-3: First Pass Yield percentage of mandrels at each inspection station[3]

The top seven lines show the first pass yield at the inspection stations as shown previously in the process flow charts (Figure 2-1 and Figure 2-2), while the last line, Assy RTY%, is the product of the above lines. The Assy RTY% can be seen to be improving over time, which is consistent with our intuition of a labor-intensive industry – the workers gain skills and experience over time, thus the quality of their work improves over time as well.

Another characteristic of the assembly line is that some processes require the operator to undergo a specialized course and obtain a certification before he is allowed to work. These processes are, namely, the full welding booths, heat treatment furnace, and the Magnetic Particle Inspection station. Certified workers are required at the heat treatment furnace as they have to configure the process parameters (temperature increases, duration of treatment) and monitor the status of the furnace once in a while to ensure that the process is going on smoothly. Moreover, as the workers have to get very near to the red-hot mandrels and furnace, they have to undergo special training to ensure their safety. Workers in all other processes do not require specialized certifications and are thus allowed to help out across different processes.

There are two consequences to this requirement. Firstly, workers will have to be employed early enough to allow for training. This is particularly true since the quality of their work will only increase to acceptable standards after a few months in the shop floor. Secondly, since only certified workers are allowed at certain processes, other workers cannot replace their positions; they can only help out as assistants.

All these characteristics of the assembly line make staffing issues more complicated, especially when large increases in demand are expected over the next few years. Using heuristics and mathematical ratios, the Production Manager has devised a manpower plan for the next three years, which is shown in Table 2-1.

Table 2-1: Manpower plan drafted by the Production Manager

Position	End 2009	End 2010	End 2011	End 2012	End 2013
Supervisors	3	4	5	6	7
Welders	10	18	20	20	26
Other Production	6	11	13	20	27
Inspectors	5	8	10	12	13
Total	24	41	48	58	73

The quality of welds is essential to the functionality of the entire mandrel, thus it is best for the welders to stay focused on their work in the welding booths. Other production workers in assembly processes before and after Full Welding (Round and Oval Mandrel Fit Up, Hot Straightening, OD Grinding, etcetera) are allowed to move away from his station to assist in another process if it is deemed necessary by the supervisors. Inspectors belong to the Quality Control department and thus are not included in the "Other Production" workers' headcount. In the assembly line, they are in charge of Hardness Test, Magnetic Particle Inspection and Pressure Test.

If we were to consider workforce flexibility and the fact that the facility runs on three shifts a day, the manpower allocation and planning problem actually becomes even more complicated. Complexity is further increased if we double the number of workers to 96 workers at the end of 2013, as suggested by Table 2-1. Therefore, there is a need to devise a more systematic method in deciding the employment, training and deployment of workers on the shop floor.

2.4 Objectives and Scope

The primary objective of this project is to reduce the cycle time of processes to meet the planned cycle times for the next few years. Cycle time is defined as the average duration taken by a process to complete operations on one mandrel. For a process that works on only one mandrel at a time, the cycle time is simply the difference between the start and end times of that station. For a batch process such as Heat Treatment, that difference in time is divided by the number of mandrels in the batch.

As dictated by the company, the planned cycle time of a particular year is 85% of the year's takt time. Takt time is the amount of time needed to produce a part in order to satisfy the rate of demand. Specifically, for the given demand forecasts, the planned cycle times for a three shift assembly line are as follows: 113min by this year, 58min in 2011, 43min in 2012 and 38min in 2013.

In support of the primary objective, the second objective would be to develop a model which will assist the Production Manager in manpower employment and deployment decisions. This model should aim to maximize the flexibility of the assembly line, yet incur minimal additions in cost of labor. It should also be a revisable model that can be changed over time, as continuous improvements are to be expected in all manufacturing lines and as the company updates its demand forecasts.

However, due to time constraint and the complexity of the entire production line, only in-house assembly processes from the fit-up booths to the pressure test bay will be considered. We do not consider machining processes prior to the assembly line and outsourced processes such as Radiography, Sand Blasting, Painting and Threading, as these are deemed out of scope for this project.

3 Literature Review

3.1 Takt time

Takt time is the amount of time that a factory is allowed to produce a unit of the product in order to meet the rate of customer demand[4].

$$\text{Takt time} = \frac{\text{Available working time per day}}{\text{Customer demand per day}} \quad (1)$$

This is a target time used to synchronize the rate of production with the rate of sales, so that over or under-production do not occur. To prevent Work-In-Process (WIP) from building up or from stocking out between processes in the production line and causing blockages/starvation to occur, all processes should be balanced such that they produce to the takt time.

3.2 Workforce Flexibility

This concept involves cross-training workers across different processes, so that they can be shifted from one process to another. Workforce flexibility can be implemented when the processes involved are labor-intensive in nature, and if bottlenecks are present in the system. Workforce flexibility allows the workers in faster processes to help out in the slower processes, achieving some form of line-balancing. In [5], Molleman and Slomp designed linear programming models and developed a hierarchical procedure for cross-training to ease the workload of the bottleneck worker.

Also, as workers are able to switch tasks rapidly, the production line will be able to respond quickly to changing demand[6]. This results in less Work-In-Process (WIP) and higher response times.

However, in [7] Slomp and Molleman has shown that there is a limit to how much cross-training should be done on the workers. Diminishing returns are observed after workers are cross-trained on several tasks. As a result, it is important to determine the optimum number of tasks that workers are cross-trained on, so as to reap the maximum benefits of cross-training.

3.3 Job Rotation Scheduling

Job rotation scheduling is closely related to cross-training, since workers have to be cross-trained before they can be rotated over several jobs. One of the main rationales behind job rotation is to minimize occupational injuries, particularly in highly repetitive work environments [8]. The situation is aggravated in workplaces where frequent manual material handling is expected. In these workplaces, back injuries are a leading cause of lost workdays[9].

Other than reducing the possibility of occupational injuries, job rotation also helps in reducing dullness from doing the same job repeatedly, thus increasing productivity and job satisfaction. It also aids in improving alertness and reduces errors[10].

3.4 Mathematical modeling for workforce flexibility

Due to the complexity of workforce flexibility, many recent researchers have focused on using linear programming or mixed integer linear programming to compute optimal or near-optimal solutions. These solutions are then used as decision-aids to the managers in planning how to cross-train workers. Stewart[11] formulated four models separately to minimize the total cost of training, maximize the flexibility of the workforce, minimize the total training time and optimize the trade-off between cost of training and the amount of flexibility achieved. To put the problem into a realistic manufacturing context, the paper also included constraints such as the amount of available production hours, production requirements and budget given.

Hertz, Lahrichi and Widmer[12] devised a mixed integer linear programming (MILP) model which balances the workload of workers across different multiple shifts without any shortages in capacity. They found that annualizing working hours is not just economically beneficial, but also allows the company to plan productive capacity to meet changes in demand, achieving flexibility. Different employment strategies such as gradual hiring and part time work were also studied with the MILP model.

4 Methodology

This chapter describes in detail the procedure used to obtain the manpower plans for the years 2011 to 2013. Data were first gathered from time study at all processes in the shop floor, as well as interviews with the production manager, supervisor and shop floor workers. The time study also revealed that the workers were not productive all the time, which is a crucial aspect to consider and will be discussed in Section 4.2. The Planned Cycle Times of each process were then calculated with the demand forecasts and compared with the manual work content obtained from the time study to formulate the manpower employment and deployment plans.

4.1 Data Collection and Analysis

The first stage of analysis entails collecting relevant data from the shop floor to further characterize the actual process flow. This also provides a benchmark for comparison of results after solutions have been developed.

A one-month long time study was conducted at all assembly and inspection processes to document the list of operations for each process. The start and end times of each operation were also recorded dutifully with a digital watch. If a worker was seen to stray away from the process, such as to help out in another process or simply to take a break, the time would be stopped and restarted only when the worker resumed the operation. All observations were made in the first shift, as the author was not allowed to enter the shop floor in the second and third shift as an intern.

As all processes were operational in the first shift, the author was able to observe multiple processes simultaneously. By standing between processes that were in close proximity to each other, the author could observe and time as many as three processes at a time. However, some processes were conducted in enclosed rooms, such as the Full Welding and Pressure Test. Observations of these processes were performed individually.

Although the company has two systems (one manual and the other computerized) to record processing times, the timings only capture the overall cycle time for each process and not the detailed tasks at each station. Moreover, some of these data may not accurately reflect the actual cycle times, as they are not always recorded faithfully at the start and end of each process.

Short interviews were also held with the workers to understand the importance of each task they carried out. This is important, as the workers are the most experienced and knowledgeable of their areas of focus. As each process involves different operations with different equipment, general questions were first put forward to the workers. These include how the process was carried out and what difficulties they faced. Other process-specific questions were then developed along the way as the workers divulged more about their work.

The workers might have deviated from the Standard Operating Procedures (SOPs) by improving the process on their own over time, or they may have grown accustomed to certain imperfections in the process. It will be critical at this point to single out these imperfections before further analysis is performed.

The individual tasks in each process were then categorized into Specialized or General Tasks. Specialized Tasks are those that have to be completed by a worker who is fixed at that station, while General Tasks can be done by general helpers, who are available to help out in other processes as well. Appendix II shows how the tasks in all processes are separated into Specialized and General Tasks, while Section 5.6 describes how this arrangement is incorporated in the manpower plans to reduce cycle times.

4.2 Proportion of productive working hours

An important factor to consider when deciding the number of workers to employ would be the actual working hours of an average worker. The takt time equation in Section 3.1 assumes that the production line is working at 100% efficiency throughout the available working hours. However, in a labor-intensive assembly line, it would be impractical to assume that the workers would work at a constant rate throughout their shift.

Other than the official breaks that are given to the workers (a 30-minute lunch break at 12 noon and two 15-minute tea breaks at 9:30am and 2:30am respectively for those in the first shift), it is normal for the workers to take occasional toilet breaks, or to stop their work to engage in short conversations with their colleagues. The proportion of time spent on these unofficial breaks may vary across different companies and different cultures.

To obtain an estimated percentage of the productive working hours in the GLM assembly line, several workers were chosen at random as subjects of observation. The time at the start of the observation was recorded and paused when the workers stop for any unofficial breaks. The timing was then restarted when work was resumed, and the time at the end of the observation was also noted. The following equation was then used to calculate the percentage of productive working hours of an average worker:

$$\text{Proportion of productive working hours} = \frac{\sum_{i=1}^{n} \frac{w}{t_e - t_s}}{n} \quad (3)$$

where w = work content, t_s = time at the start of the observation, t_e = time at the end of the observation and n = number of observations.

A person's behavior is often affected when he is being observed by someone, particularly a stranger. Thus, before the time study was carried out, the author had spent a month visiting the shop floor to build rapport with the workers and to conduct the short interviews in a casual setting. This helped the workers to familiarize themselves with the author and reduced any psychological uneasiness during the actual time study. Moreover, during the time study, the author often observed multiple processes at once and was thus a distance away from the workers. By maintaining a physical distance away from them, the workers should have been able to behave as they normally would, resulting in sufficiently representative results in the calculation of the proportion of productive working hours.

4.3 Planned Cycle Time

The concept of takt time was introduced in Section 3.1 as a target time to produce a part in order to match the rate of customer demand. However, to obtain a more realistic and accurate gauge of how fast each process should be in the assembly line, two corrective factors have to be used in conjunction with Equation 1 to attain the Planned Cycle Time for each process.

$$\text{Planned Cycle Time} = \frac{\text{Available working time per day}}{\text{Customer demand per day}} \times \text{Inef iciency Factor} \times \text{Proportion of productive hours} \quad (4)$$

The Inefficiency Factor is a ratio utilized by the company to account for equipment downtimes, rework and variations in processing times between mandrels. As mentioned in Section 2.4, this ratio was dictated by the management to be 0.85.

4.4 Formulation of manpower plans

Several assumptions were made during the formulation of manpower plans. Firstly, we assume that all forecasts on future demand are accurate. All calculations on takt times and Planned Cycle Times were based on these forecasts. We also assume that no major changes are made to processes within the next few years, which will revolutionize the manual work contents and thus result in a change in need for manpower.

From the time study mentioned in Section 4.1, the manual work content of each process was calculated. This time is compared to the Planned Cycle Time for a shift. If the manual work content exceeds the Planned Cycle Time, it means that the process is too slow to fulfill the rate of demand. A second shift will be added to this process to reduce the Planned Cycle Time by half. This continues till all three shifts have been allocated to the process. When this happens, another worker will have to be added to a shift to reduce the Planned Cycle Time even further.

This framework ensured that the primary objective of achieving the planned cycle time was met, and that a solution with minimal number of workers was generated, sufficient to meet the expected demand over the next few years.

In order to improve the utilization rate of workers, workforce flexibility was incorporated into the manpower plan by grouping the processes into clusters and allowing the workers within a cluster to move across different processes in the cluster.

General Tasks in the clusters were then combined to see if there is sufficient work to be allocated to a full-time General Worker. If not, these tasks will remain in the process to be performed by the worker assigned to the particular process.

5 Results and Discussion

This chapter presents and discusses the results that are derived from data in Appendix I and II.

5.1 Proportion of productive working hours

We found that for a normal shift of eight hours with an hour of official breaks (lunch and tea breaks), the workers spent another 1.23 hours on unofficial breaks on average. The remaining 5.77 hours are spent on working in their own stations. Figure 5-1 shows a breakdown of the timings.

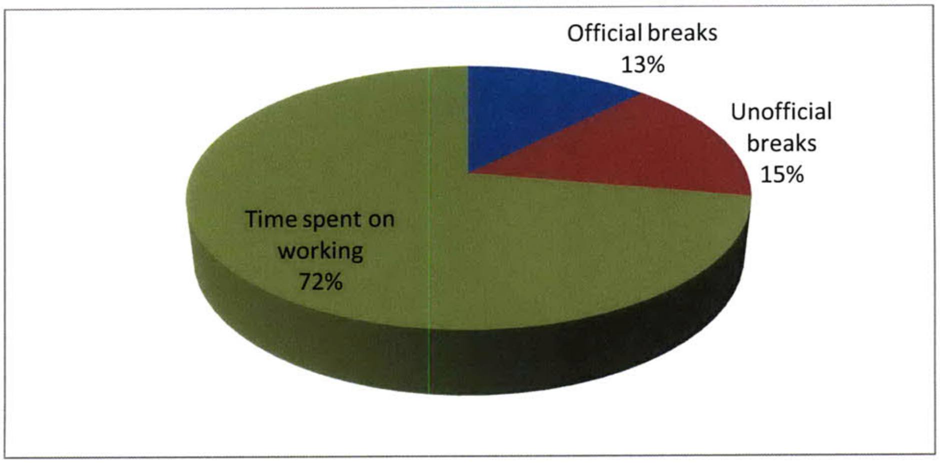

Figure 5-1: Breakdown of working hours for a normal shift

The proportion of time spent on working can be imagined as the "uptime" of the workers, when they are actually performing value-adding activities to the mandrels in their station. It may seem tempting to try and reduce the amount of unofficial breaks by asking the workers to refrain from unnecessary conversations and toil without respite. However, this is impractical and inhumane, since the workers cannot and should not be seen as machines. The harsh and dangerous working environment in the assembly line makes it necessary for workers to take a rest once in a while to prevent work fatigue and injuries.

This particular analysis will help in understanding how efficient the workers are, and how many more workers we should employ to cope with the expected increase in demand in the near future.

5.2 Planned cycle time analysis

Figure 5-2 shows the demand forecast of oval and round mandrels from Year 2010 to 2013. Demand for both round and oval mandrels is expected to increase by 205% and 170% respectively by the year 2013, exerting strain on the current manufacturing capacity.

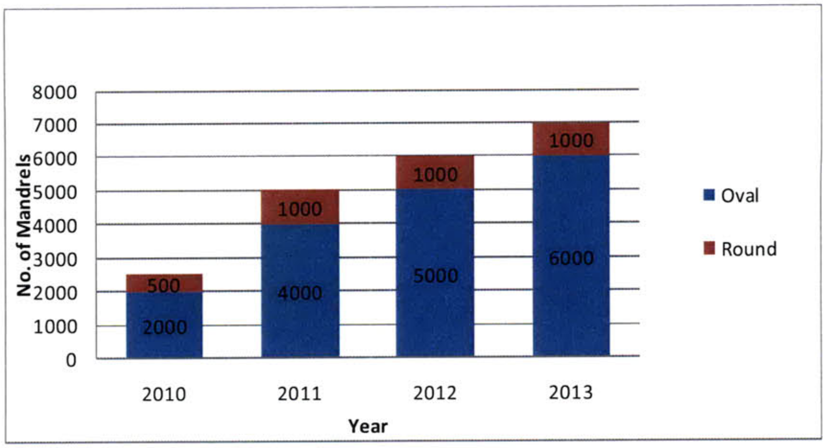

Figure 5-2: Demand forecast of GLMs

With the Equation 1 shown in Section 3.1, the takt times of three-shift, two-shift and single-shift processes can be calculated for each year till 2013, with the assumption that the assembly line operates 5.5 days a week. This will be further explained in Section 5.4. The takt times are illustrated in Figure 5-3, Figure 5-4 and Figure 5-5 respectively. It can be seen that as demand increases across the years, the takt time has to decrease so as to produce mandrels sufficiently fast to satisfy customer orders.

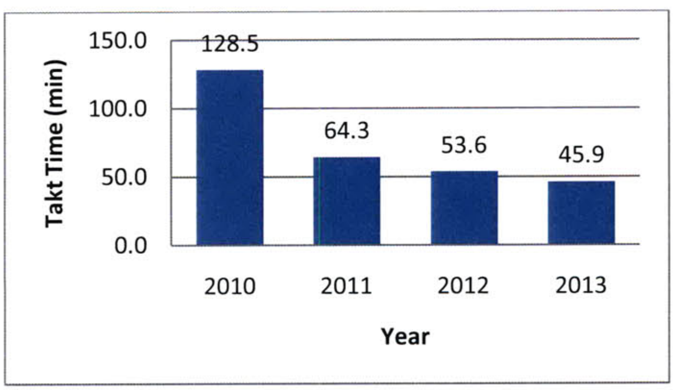

Figure 5-3: Takt times for 3-shift processes

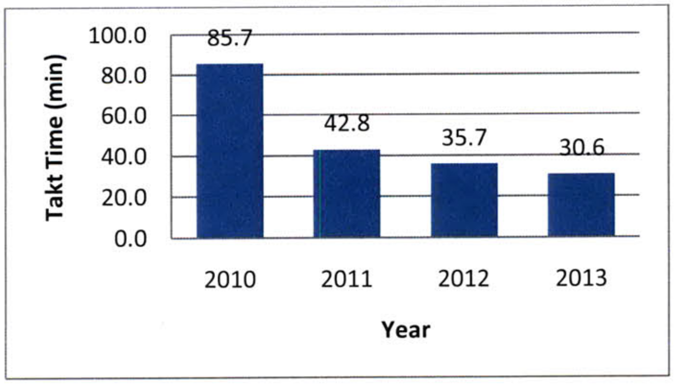

Figure 5-4: Takt times for 2-shift processes

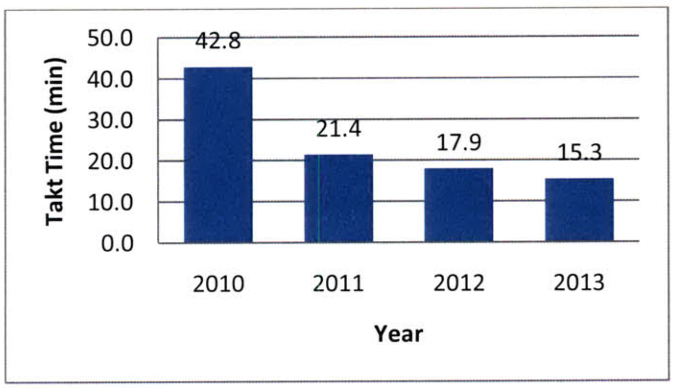

Figure 5-5: Takt times for 1-shift processes

Equation 4 was then used to calculate the Planned Cycle Time for each process. The Inefficiency Factor was given a value of 0.85 by the management. The proportion of productive hours is a ratio explained in the previous section, and is given a value of 0.72. The Planned Cycle Times for each process is tabulated in Table 5-1.

Table 5-1: Planned Cycle Times (in minutes) from 2010 to 2013

Planned Cycle Times (min)														
	Year	Projected Demand	No. of Shifts (5 days a week)			No. of Shifts (5.5 day a week)			No. of Shifts (6 day a week)			No. of Shifts (7 days a week)		
			3	2	1	3	2	1	3	2	1	3	2	1
Ovals	2010	2000	101.0	67.3	33.7	112.5	75.0	37.5	124.0	82.6	41.3	146.9	97.9	49.0
	2011	4000	50.5	33.7	16.8	56.2	37.5	18.7	62.0	41.3	20.7	73.5	49.0	24.5
	2012	5000	40.4	26.9	13.5	45.0	30.0	15.0	49.6	33.1	16.5	58.8	39.2	19.6
	2013	6000	33.7	22.4	11.2	37.5	25.0	12.5	41.3	27.5	13.8	49.0	32.6	16.3
Rounds	2010	500	404.1	269.4	134.7	450.0	300.0	150.0	495.8	330.6	165.3	587.6	391.7	195.9
	2011	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
	2012	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
	2013	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
Total	2010	2500	80.8	53.9	26.9	90.0	60.0	30.0	99.2	66.1	33.1	117.5	78.3	39.2
	2011	5000	40.4	26.9	13.5	45.0	30.0	15.0	49.6	33.1	16.5	58.8	39.2	19.6
	2012	6000	33.7	22.4	11.2	37.5	25.0	12.5	41.3	27.5	13.8	49.0	32.6	16.3
	2013	7000	28.9	19.2	9.6	32.1	21.4	10.7	35.4	23.6	11.8	42.0	28.0	14.0

The Planned Cycle Times for Oval, Round and Total (both types of mandrels) are shown, as some processes were dedicated to one type of mandrel, while the other processes were shared between both the oval and round mandrels.

Specifically, the following processes were dedicated to oval mandrels:

1. Oval Mandrels Fit Up
2. Plasma Cutting
3. Pocket Fitting

The following processes were dedicated to round mandrels:

1. ID Welding
2. Round Mandrels Fit Up

The other processes are shared between both oval and round mandrels:

1. Full Welding
2. Hot Straightening
3. OD Grinding
4. MPI
5. Heat Treatment
6. Hardness Test
7. Cold Straightening
8. OD Drift
9. Pressure Test

We see from Table 5-1 that the Planned Cycle Time depends on the projected demand for a particular year, the number of working days per week and the number of shifts per day. As projected demand increases over the years, the Planned Cycle Time decreases as the assembly line will have to produce mandrels at a faster rate to meet up with the rate of demand. On the other hand, increases in number of working days per week or number of shifts per day will both augment the available working hours, allowing the assembly line to produce at a slower (and more reasonable) rate. Although there are normally five working days a week, the number can be increased by asking the workers to work overtime before or after their normal shifts, or asking them to return on weekends to work. This strategy is possible but not advisable, and will be discussed further in Section 5.4.

5.3 Average manual work content of each process

A series of tasks are performed on each mandrel as they arrive at each process, such as loading, grinding, calibrating, welding, et cetera. As mentioned previously, most of these tasks are performed by workers; very few are automated. Even these few automated tasks, such as those in the plasma cutting and pressure testing processes, have to be closely monitored by the workers. Appendix II shows the list of tasks that are executed at each process and the average task times taken by different mandrels. The average manual work content per mandrel of each process is illustrated in Figure 5-6.

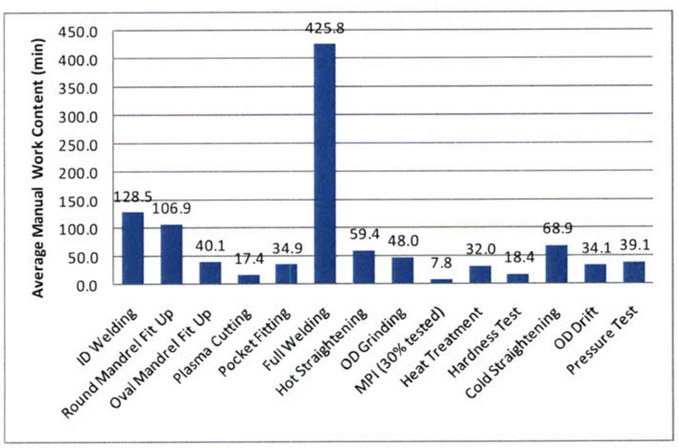

Figure 5-6: Average manual work content per mandrel of processes

The average manual work content at MPI has been multiplied by 0.3, since only 30% of the mandrels were required to go through MPI. Out of all the processes, only Heat Treatment was a batch process where multiple mandrels were secured to a basket before being lowered into the furnace. During the entire heat treat cycle, the basket was transported several times from one furnace to another, or to a polymer/air cooling tank. All these manually operated transportations took 196 minutes in a cycle, and this time is divided by six, which was the average number of mandrels that were carried in the basket per cycle.

It is evident that the Full Welding process requires the most manual work per mandrel. This is due to the fact that welding is a slow, serial process that acts on a small spot relative to the total area of the mandrel.

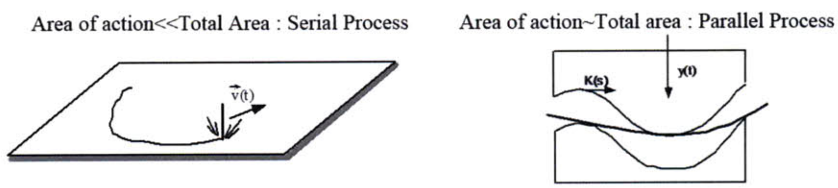

Figure 5-7: Serial and parallel processes [13]

Moreover, the following factors make welding of mandrels a slow process which is difficult to automate:

1. Components of mandrels are sometimes made of materials with different heat codes
2. Welding gaps between components often have inconsistent widths
3. Challenging geometry of the mandrels
4. Uneven weld surfaces and the presence of tack welds, which require substantial grinding throughout the welding process

As a result, increasing the number of welders might be the only simple way to reduce the cycle time of the welding process substantially.

Although the other processes have significantly smaller manual work contents as compared to Full Welding, most of them are still too large to meet the projected demand with the current manufacturing capacity. Capacity thus has to be enhanced by increasing the number of shifts and/or the number of workers per shift. This will be elaborated further in the Section 5.6.

5.4 Baseline analysis

To determine if the model of work content accurately reflects the actual operations of the shop floor, we used it to calculate a theoretical number of workers required in order to achieve the actual throughput of mandrels in the previous month. The calculations were done in an Excel spreadsheet, shown in Appendix II.

Table 5-2: Summary of current manpower status

No.	Cluster Name	Processes	Manpower (Actual)	Manpower (Calculated)
1	Full Welding	Full Welding	8	12
2	Other Production	ID Welding Round Mandrel Fit Up Oval Mandrel Fit Up Plasma Cutting Pocket Fitting Hot Straightening OD Grinding Heat Treatment Cold Straightening OD Drift	17	12
3	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test	3	2
		Total	28	26

Table 5-2 compares the theoretical number of workers required with the actual number of workers that are deployed on the shop floor. The numbers appear to coincide fairly well, suggesting that the model is sufficiently accurate and realistic for drafting manpower plans for the following years. However, twelve welders were predicted with the model, which is 50% more than the actual number of welders currently employed. This explains why the welders have been working overtime for at least the past month. The production supervisor has commented that the Full Welding process was understaffed, thus the welders have to work overtime to meet up with the demand.

We noticed during the time study that all the workers have been working overtime for at least a month. They worked for an extra two hours on several weekdays, and everyone had to return for a full day on Saturday. Thus, when calculations were done for the theoretical number of workers in Table 5-2, it was assumed that the workers worked six to seven days a week.

This situation may not be sustainable for the long term, as hints of fatigue and lethargy could already be seen on some of the workers. The incoming increase in demand will directly translate into a larger workload for the workers, aggravating the situation further. We therefore decided that manpower plans of future years should be calculated with the assumption that workers work five to five and a half days a week. The extra half day is included in the calculations as the management would like to maximize the utilization rate of workers. If only five working days are considered in the manpower plans, workers might become idle during periods of low demand. The management deems the idling of workers as waste, which should be avoided.

Another observation made during the time study was that several processes required significant grinding of mandrels as the initial preparatory steps of the processes. Other than taking up the worker's time, it also caused the mandrel to occupy the workstation for a period of time longer than necessary. This can be seen in Appendix I, the work content of all processes in the assembly line. If the grinding operations can be performed by another worker before the mandrels enter the individual processes, the cycle time will be effectively reduced. This will be discussed in further details in Section 5.6.

5.5 Employment and deployment of workers

To determine exactly how many workers should be employed over the next few years and how they should be trained and deployed in the shop floor, all assembly processes in the shop floor are grouped into clusters of two to three processes, according to their sequence in the process flow and their location in the shop floor. Table 5-3 shows how the clusters are configured.

Table 5-3: Proposed clusters and their constituent processes

No.	Cluster Name	Processes
1	Round Mandrel Connection	ID Welding Round Mandrel Fit Up
2	Oval Mandrel Connection	Oval Mandrel Fit Up Plasma Cutting Pocket Fitting
3	Full Welding	Full Welding
4	Pre-Heat Treatment	Hot Straightening OD Grinding
5	Post-Heat Treatment	Heat Treatment Cold Straightening OD Drift
6	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test

There are several advantages to cluster processes in this manner. As mentioned in Section 3.2, diminishing returns result as the level of cross-training exceed a certain number of tasks, as workers tend to lose focus in their work. By grouping just two or three related processes in a cluster, the workers will be able to concentrate better and yet allow for some degree of workforce flexibility within the cluster. Job rotation, which was discussed in Section 3.3, can also be implemented in the cluster to mitigate the risk of occupational injuries and improve alertness.

Practicing workforce flexibility within the small clusters will also help to improve the utilization rate of workers. Table 5-4 shows the difference in worker utilization rates before and after implementing workforce flexibility in the Oval Mandrel Connection cluster in the year 2012. It can be seen that one less worker will be required in the cluster if workforce flexibility is practiced, improving the utilization rate from 0.82 to 0.94.

Table 5-4: Utilization rates of Oval Mandrel Connection cluster with and without workforce flexibility

	Without workforce flexibility	With workforce flexibility
Total daily work content in cluster (min)	1940	
No. of workers required	8	7
Available productive time (min)	2353	2059
Utilization rate	0.82	0.94

Moreover, as the number of workers in the assembly line is expected to increase considerably over the years, problems may arise when it comes to manpower control and communication. When such a scenario arises, team leaders can be appointed in each of these clusters to aid in communicating instructions and quality concerns from the management to the other workers. Conversely, feedback can be collected from the workers and conveyed back to the management through these team leaders.

5.6 Manpower plan for 2011

Table 5-5 illustrates the number of workers that should be deployed to each cluster, in order to achieve the Planned Cycle Times. A total of 56 workers will be required in the assembly line.

Table 5-5: Manpower plan for 2011

No.	Cluster Name	Processes	Manpower		
			1st Shift	2nd Shift	3rd Shift
1	Round Mandrel Connection	ID Welding Round Mandrel Fit Up	1	1	1
2	Oval Mandrel Connection	Oval Mandrel Fit Up Plasma Cutting Pocket Fitting	2 (1 is a grinder)	2 (1 is a grinder)	1
3	Full Welding	Full Welding	9	9	9
4	Pre-Heat Treatment	Hot Straightening OD Grinding	3 (1 is a grinder)	2	2
5	Post-Heat Treatment	Heat Treatment Cold Straightening OD Drift	3	3	3
6	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test	2	2	1
		Total	56		

The number of workers has been evenly distributed across three shifts, in order to minimize the number of workstations required at each of the processes. This is an important consideration as the shop floor has a limited area for expansion. It would be infeasible to allocate all the workers to one shift as it would lead to a waste of space, idleness during the other two shifts and higher WIP. For example, in the Pre-Heat Treatment cluster, if all seven workers are allocated to the first shift, there must be seven workstations for them to work on. On the second and third shifts, these workstations will be totally unoccupied and idle. At the same time, if the upstream clusters are still working around the clock, WIP will pile up at this cluster during the second and third shifts. It is thus beneficial to have an equal and consistent number of workers across all three shifts in each cluster.

It was discussed in Section 5.4 that significant grinding was required prior to several processes. These have been classified as General Tasks that can be taken out of the process and managed by a separate worker. In this manpower plan, a total of 3 grinders will be required, and their job-scope is listed in Table 5-6.

Table 5-6: Job scopes of grinders in 2011

	Grinder 1	Grinder 2	Grinder 3
Job scope	**Oval Fit Up:** Grind upper swages, lower swages, and body pipes **Pocket Fitting:** Grind pockets	**Pocket Fitting:** Grind body pipes **MPI:** Grind ends of mandrels **Hardness Test:** Grind inspection points **Pressure Test:** Grind swages and pocket	**Hot Straightening:** Grind interior weld surfaces

There are several advantages to having these grinders in the shop floor:

1. Allow the workers at the processes to focus better on the main operations.
2. Reduce the cycle time of processes.
3. Savings in cost of labor, as grinding requires little or no training. Grinders can be paid a lower salary relative to other skilled workers.

It can be seen in Table 5-7 that the worker utilization rate of each cluster is relatively high, ranging from 0.77 to 0.99.

Table 5-7: Utilization rates of clusters in 2011

	Round Mandrel Connection	Oval Mandrel Connection	Full Welding	Pre-Heat Treatment	Post-Heat Treatment	Inspection
Utilization Rate	0.77	0.98	0.99	0.96	0.94	0.82

5.7 Manpower plan for 2012

Table 5-8 illustrates the number of workers that should be deployed to each cluster, in order to achieve the Planned Cycle Times in the year 2012. A total of 75 workers will be required in the assembly line.

Table 5-8: Manpower plan for 2012

No.	Cluster Name	Processes	Manpower		
			1st Shift	2nd Shift	3rd Shift
1	Round Mandrel Connection	ID Welding Round Mandrel Fit Up	2	1	1
2	Oval Mandrel Connection	Oval Mandrel Fit Up Plasma Cutting Pocket Fitting	3 (1 is a grinder)	2 (1 is a grinder)	2
3	Full Welding	Full Welding	12	12	12
4	Pre-Heat Treatment	Hot Straightening OD Grinding	4 (1 is a grinder)	3 (1 is a grinder)	3
5	Post-Heat Treatment	Heat Treatment Cold Straightening OD Drift	4	4	4
6	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test	2 (1 is a grinder)	2	2
		Total	75		

Similarly, Table 5-9 shows how many grinders should be employed and their respective job-scopes.

Table 5-9: Job scopes of grinders in 2012

	Grinder 1 and 2	Grinder 3 and 4	Grinder 5
Job scope	**Oval Fit Up:** Grind upper swages, lower swages, and body pipes **Pocket Fitting:** Grind pockets and body pipes	**Hot Straightening:** Grind interior weld surfaces	**MPI:** Grind ends of mandrels **Hardness Test:** Grind inspection points **Pressure Test:** Grind swages and pocket **Assist Grinders 3 and 4**

It can be seen in Table 5-10 that the worker utilization rate of each cluster is relatively high, ranging from 0.78 to 1.0.

Table 5-10: Utilization rates of clusters in 2012

	Round Mandrel Connection	Oval Mandrel Connection	Full Welding	Pre-Heat Treatment	Post-Heat Treatment	Inspection
Utilization Rate	0.78	0.94	1.0	0.91	0.95	0.92

5.8 Manpower plan for 2013

Table 5-11 illustrates the number of workers that should be deployed to each cluster, in order to achieve the Planned Cycle Times. A total of 82 workers will be required in the assembly line.

Table 5-11: Manpower plan for 2013

No.	Cluster Name	Processes	Manpower		
			1st Shift	2nd Shift	3rd Shift
1	Round Mandrel Connection	ID Welding Round Mandrel Fit Up	2	1	1
2	Oval Mandrel Connection	Oval Mandrel Fit Up Plasma Cutting Pocket Fitting	3 (1 is a grinder)	3 (1 is a grinder)	2
3	Full Welding	Full Welding	14	13	13
4	Pre-Heat Treatment	Hot Straightening OD Grinding	4 (1 is a grinder)	4 (1 is a grinder)	3 (1 is a grinder)
5	Post-Heat Treatment	Heat Treatment Cold Straightening OD Drift	5	4	4
6	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test	2 (1 is a grinder)	2	2
		Total	82		

Table 5-12: Job scopes of grinders in 2013

	Grinder 1 and 2	Grinder 3, 4 and 5	Grinder 6
Job scope	**Oval Fit Up:** Grind upper swages, lower swages, and body pipes **Pocket Fitting:** Grind pockets and body pipes	**Hot Straightening:** Grind interior weld surfaces	**MPI:** Grind ends of mandrels **Hardness Test:** Grind inspection points **Pressure Test:** Grind swages and pocket

Table 5-13: Utilization rates of clusters in 2013

	Round Mandrel Connection	Oval Mandrel Connection	Full Welding	Pre-Heat Treatment	Post-Heat Treatment	Inspection
Utilization Rate	0.94	0.92	1.0	0.94	1.0	1.0

5.9 Evaluation of proposed manpower plans

As discussed, forming clusters of processes allows the workers to focus better, but still allows for the implementation of job rotation and workforce flexibility. These two manpower scheduling concepts can help to reduce the risk of occupational injuries and improve the utilization rate of workers, respectively. In addition, appointing team leaders in each cluster will aid in communication and manpower control as the number of shop floor workers increases multifold.

The introduction of grinders as low-skilled workers is a strategy to reduce the cost of labor and the cycle time of processes, enabling the entire assembly line to achieve the takt time ultimately.

Currently, a regular workweek consists of 5 working days. Any extra working hours or days are regarded as overtime. The manpower plans proposed in this thesis assume that there are five regular working days a week and just half a day of overtime in order to reduce the amount of potential overtime hours required. This brings about several advantages.

1. Most evidently, reducing the number of overtime hours results in a lower overtime labor cost. Workers are paid 50% more than their usual rates when they work overtime, but they do not work 50% faster during those extra hours. Overtime can therefore be seen as a form of waste and should be reduced.
2. In the harsh environment of the assembly line, fatigue sets in easily on the workers. Elongating the working hours with overtime will only aggravate the fatigue further, resulting in a further decrease in productivity. This is supported by an observation made during the time study. Towards the end of the shift, especially during the overtime hours, the workers took breaks longer than stipulated, and stopped more frequently for conversations with each other. This further verifies the point that overtime is wasteful and should be minimized.
3. Overtime should only be viewed as an additional overrun of capacity, which should only be used to satisfy periods of high demand. By planning for only five and a half working days a week,

there will be sufficient buffer for the assembly line to utilize the remaining time as overtime to cope with any short term increases in demand.

As the calculations were derived from time study data collected by the author, and corrective ratios were utilized in the calculations, the results should reflect the actual operations and requirements of the assembly line. Since these results were computed from the projected demand of mandrels, the manpower plans should provide sufficient workforce capacity should the demand forecasts materialize.

However, this also means that the soundness of the manpower plans depends on the accuracy of the demand forecasts. If the actual demand is lower than expected, we may be left with a large number of workers, which may pose a huge liability to the company. It is therefore critical to revise the manpower plans when updated and more accurate demand forecasts are obtained for the future years.

6 Recommendations

This section summarizes the respective manpower plans till the year 2013, as presented and discussed in the previous chapter. Several potential areas of improvement were also identified and the respective recommendations will be proposed in this chapter to reduce the work content of processes. If successful, these improvements will translate to a reduction in the calculated manpower plans.

6.1 Summary of Manpower Plan

Table 6-1 shows the number of workers that should be employed and deployed in each of the six proposed clusters in the assembly line. For more details on how the workers are allocated into the three shifts, please refer to Sections 5.6 to 5.8.

Table 6-1: Summary of manpower plans from 2011 to 2013

No.	Cluster Name	Processes	Manpower for Year			
			2010 (Actual)	2011	2012	2013
1	Round Mandrel Connection	ID Welding Round Mandrel Fit Up	7	3	4	4
2	Oval Mandrel Connection	Oval Mandrel Fit Up Plasma Cutting Pocket Fitting		5 (2 are grinders)	7 (2 are grinders)	8 (2 are grinders)
3	Full Welding	Full Welding	8	27	36	40
4	Pre-Heat Treatment	Hot Straightening OD Grinding	10	7 (1 is a grinder)	10 (2 are grinders)	11 (3 are grinders)
5	Post-Heat Treatment	Heat Treatment Cold Straightening OD Drift		9	12	13
6	Inspection	Hardness Test Magnetic Particle Inspection Pressure Test	3	5	6 (1 is a grinder)	6 (1 is a grinder)
		Total	28	56	75	82

6.2 Cycle time reduction at Cold Straightening

6.2.1 Problem

At the Cold Straightening station, mandrels were subjected to ID drift tests to examine if the interior of the mandrels were axially straight. Pressure was applied to the mandrels at room temperature if they were found to be bent or twisted, till they were straightened to the point when the ID drift bar could pass through the mandrel smoothly. It was observed that a substantial amount of time was spent in holding the bent mandrels under pressure, as the workers believed that this would help to reduce spring-back as the pressure was released. In other words, the general belief was that the longer the holding time, the smaller the spring-back. Approximately half the processing time at this station could be attributed to the holding time.

6.2.2 Recommendations

The holding time in fact does not significantly affect the amount of spring-back on the mandrels. Mori, Akita and Abe have shown that the forming speed and holding time have very little effect on the amount of spring-back seen on steel sheets[14]. If the pressure is kept constant during the hold time at room temperature, the stainless steel does not experience any creep or exhibit any visco-elastic behavior that allows the spring-back to be reduced. The waiting time can simply be eliminated, reducing the cycle time by about 50% effectively.

6.3 Cycle time reduction at OD Drift

6.3.1 Problem

Two methods of OD Drift were available:

1. Vertical OD Drift – for OD Drift diameter above 4.767 inches
2. Horizontal OD Drift – for OD Drift diameter 4.767 inches or below

Both methods of OD Drift required a considerable amount of time and effort in setting up the OD Drift bars, and loading and unloading mandrels into OD drift bars. This was especially true for the horizontal OD Drift, where the worker would have to manually carry and push the mandrels into the OD Drift bar several times manually, without the help of a crane, to locate areas on the mandrels that require grinding. These mandrels were heavy loads that caused strain on the worker's body. Moreover, there were times when mandrels got wedged within the OD Drift bar and the worker would have a difficult time removing the mandrel.

6.3.2 Recommendations

A long wooden rule can be used as a gauge to check the straightness of mandrels and aid in detecting areas to grind. This technique is not meant as a substitute to replace the OD Drift process, as OD Drift is the most definite way of ensuring that the mandrels have an axially straight exterior. The worker should still carry out the traditional OD Drift, but use the wooden rule during the process to reduce the number of times he has to insert and remove the mandrels from the OD Drift bar.

6.4 Verifying part routings before commencing operations

6.4.1 Problem

It has been observed that the routings were seldom checked just before/after work was done on the mandrels, at most of the assembly and inspection stations. This caused some mandrels to be processed with wrong tools or parameters. Costly consequences result, such as rework, scrap, or customer complaints.

6.4.2 Possible causes

There are several plausible reasons why the routings are not checked before the mandrels were processed at each of the work stations.

1. The operators do not wish to lose their momentum between mandrels. Immediately after they complete one mandrel, they wish to start on the next one as soon as possible. This is especially true for the hardness test, MPI, OD drift and cold straightening stations, as they share a common crane. Once they unload a mandrel with the crane, they'll want to load another mandrel onto their station before they lose possession of the crane. And once they have a mandrel sitting in their station, they'll want to start working on it as soon as possible. As a result, documentation work seems to get neglected.
2. The routings for assembly operations are all centralized at a shelf just beside the fit-up station. It might have been designed this way because mandrels in a single work order are often split up across different stations. Centralizing the location of routings will actually make them easier to find and prevent the routings from getting lost. However, this also means that the routings are a distance away from the individual work stations. This makes it a little inconvenient for the operators to walk to and from their stations and the shelf of routings.
3. The operators are gaining experience from working in the shop floor, and they make assumptions about the processing parameters from what they know about the mandrels.

Instead of referring to the routings, they'll recall what they have done to identical mandrels in the past.

6.4.3 Recommendations

The workers can possibly be made to check the routings by enforcing discipline and more importantly, letting them know why this procedure is important. Some of the operators do not even know how the mandrels work out in the field; thus they are unable to link the importance of their work to the final product. Educating them on this might improve their sense of pride and quality of work.

Moreover, the routings can be made more accessible to the operators. Instead of centralizing the routings, they can be made to flow with the mandrels. For example, for a work order of four mandrels, four identical copies of the routings can be made and each of them stuffed into the mandrels.

A barcode scanning system can also be installed in the shop floor. A barcode can be stuck or stenciled (in brail form) onto each of the mandrels. Each station can have one of these barcode scanning machines, or two stations can share one. When a mandrel arrives at a particular process, the worker can simply scan the barcode on the mandrel and the parameters relevant to that process will be shown to him. He can be asked to scan the mandrel again after the process is complete on the mandrel; in this way, both the start and end times will be captured automatically by the system. This barcode scanning system has numerous advantages:

1. Operators will not need to spend too much time on looking for routings or doing documentation work. Scanning the barcode will retrieve the routings immediately for their reference.
2. This system will be able to replace the Production Control Board entirely. The start and end times of each mandrel will be entered accurately, and there will not be a need to type in the entries manually every week.
3. Errors will be greatly reduced. Some mandrels are rather badly rusted and the stenciled numbers become illegible. By eliminating reading, writing and manual typing of numbers, there will be no wrong entries.
4. This system will provide real-time updates of where the mandrels are. The WIP board will not have to be updated manually, and will definitely be more accurate.

5. Mandrels that are missing in the shop floor can be easily found. There were times when mandrels get lost somewhere in the shop, and a lot of time is wasted on hunting for it. Such a system will tell the management exactly where the mandrel was last processed.

7 Conclusion

7.1 Conclusion

This thesis has presented a practical framework for calculating the manpower plan of the Gas Lift Mandrel assembly line to fulfill the projected demand of mandrels till the year 2013. Other than suggesting the number of workers to employ, this thesis also considered the training and deployment of workers across all processes in the assembly line.

Two manpower scheduling concepts were incorporated in the manpower plan, such as Job Rotation and Workforce Flexibility to optimize the rate of utilization, human performance and well-being. In particular, it has been shown that by clustering processes together and allowing the workers to move across processes within each cluster, the utilization rate can be increased to more than ninety percent.

A new position of grinders has also been proposed to assist in various grinding operations in the assembly line. By performing the grinding operations prior to the processes, these grinders help the workers at individual processes focus better on the main operations in their work stations. Removing the grinding operations from the main processes also effectively reduces the cycle times, making it easier to achieve the Planned Cycle Times. In addition, since these grinders do not require special skills like the other workers, they incur a lower cost of labor.

Other than manpower planning, this thesis has also identified several potential areas of improvement to reduce the work content of processes. Specifically, they include eliminating the holding time at Cold Straightening, utilizing a wooden rule at OD Drift to aid the worker in gauging the straightness of mandrels and locate grinding areas, and implementing a barcode scanning system to display routings.

7.2 Future Work

As more accurate forecasts of the projected demands are obtained over time, the manpower plans will have to be revised with the methodology presented in this thesis. This will ensure that the right number of workers are employed and deployed to each cluster to satisfy the rate of customer demand. Proposed scheduling concepts such as workforce flexibility and job rotation should also be implemented in these revised plans to bring about maximum worker utilization and productivity.

This thesis has also identified processes with high manual work contents, which can potentially be shortened by continuous improvement projects. Some of these processes include Full Welding, ID Welding and Round Mandrel Fit-up.

A process worthy of immediate investigation would be Cold Straightening, where there is prospective time savings of up to 50%. An experiment should be carried out in the shop floor to determine if the spring-back of mandrels is truly independent of the holding time. If the hypothesis is true, cycle time of this process will be halved, and the worker can be freed up to work on other processes.

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Appendix I – Compiled data of GLM assembly processes

Table I-1: Compiled data of GLM assembly processes

Round Mandrel Fit Up	
Steps	**Time (sec)**
Load upper swage	114
Load discriminator	74
Load lower swage	81
Air blow	35
Check drawings	281
Inspect parts	400
Align parts	1042
Tack weld	3377
Documentation	513
Stencil numbers on mandrel	402
Unload onto trolley	96
Total processing time(sec)	**6415**
Total processing time(h:mm:ss)	**1:46:55**

Specialised Task
General Task

Oval Mandrel Fit Up						
Steps	**Time (sec)**	**Time (sec)**	**Average**	**Standard Dev**	**Max**	**Min**
Load upper swage	31	11	21	14	31	11
Grind	234	249	241	11	249	234
Unload	11	15	13	3	15	11
Load lower swage	40	19	29	15	40	19
Grind	193	217	205	17	217	193
Unload	17	12	14	4	17	12
Load body pipe	89	102	95	9	102	89
Grind	285	202	244	59	285	202
Air blow	40	16	28	17	40	16
Wipe body pipe and check number	93	30	61	45	93	30
Level body pipe	100	152	126	37	152	100
Fit upper swage	423	250	336	122	423	250
Tack weld upper swage	498	141	320	252	498	141
Fit lower swage	136	62	99	52	136	62
Tack weld lower swage	68	148	108	57	148	68
Documentation	170	64	117	75	170	64
Stencil serial no. onto mandrel	327	110	219	153	327	110
Spray paint on end of mandrel		14	14		14	14
Stamp	57	47	52	7	57	47
Unload	92	50	71	30	92	50
Total processing time(sec)	**2904**	**1911**	**2408**	**702**	**2904**	**1911**
Total processing time(h:mm:ss)	**0:48:24**	**0:31:51**	**0:40:07**	**0:11:42**	**0:48:24**	**0:31:51**

Specialised Task
General Task

Plasma Cutting								
Steps	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Average**	**Standard Dev**	**Max**	**Min**
Load	40	169	40	37	72	65	169	37
Set up program	88			65	76	16	88	65
Set up fixture	237	319	113	112	195	101	319	112
Trial run		177		346	262	120	346	177
Calibrate	151	205		70	142	68	205	70
Fill water			152	101	126	36	152	101
Cut	271	65	150	179	166	85	271	65
Unload pocket	50	232	34	90	101	90	232	34
Unload mandrel to wash	56	94	100	61	78	22	100	56
Wash	47	144	42	22	64	55	144	22
Load onto bench	25	38	48	17	32	14	48	17
Total processing time(sec)	**965**	**1443**	**679**	**1100**	**1047**	**317**	**1443**	**679**
Total processing time(h:mm:ss)	**0:16:05**	**0:24:03**	**0:11:19**	**0:18:20**	**0:17:27**	**0:05:17**	**0:24:03**	**0:11:19**

Specialised Task
General Task

Pocket Fitting								
Steps	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Average**	**Standard Dev**	**Max**	**Min**
Grind pocket	317	355	356		343	22	356	317
Grind body pipe	671	22	893	589	544	371	893	22
Position body pipe	11		135		73	88	135	11
Load pocket	42	36	54	184	79	70	184	36
Fit pocket	150	222	555	253	295	179	555	150
Tack weld (and grind)	565	417	545	664	548	102	664	417
Grind off end tacks	54	55	39	55	51	8	55	39
Documentation	431	198	133	167	232	135	431	133
Unload	40	78	56	34	52	20	78	34
Total processing time(sec)	**2281**	**1383**	**2766**	**1946**	**2094**	**581**	**2766**	**1383**
Total processing time(h:mm:ss)	**0:38:01**	**0:23:03**	**0:46:06**	**0:32:26**	**0:34:54**	**0:09:41**	**0:46:06**	**0:23:03**

Specialised Task
General Task

Full Welding									
Steps	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Average**	**Standard Dev**	**Max**	**Min**
Load mandrel and Documentation	1638	2033				1836	279	2033	1638
Preheat mandrel, Grind and Weld	25688	24629	18291	28662	20709	23596	4111	28662	18291
Unload mandrel	109	292	284			228	103	292	109
Total processing time(sec)	**27435**	**26954**	**20375**	**30462**	**22509**	**25547**	**4052**	**30462**	**20375**
Total processing time(h:mm:ss)	**7:37:15**	**7:29:14**	**5:39:35**	**8:27:42**	**6:15:09**	**7:05:47**	**1:07:32**	**8:27:42**	**5:39:35**

Specialised Task
General Task

Hot Straightening

Steps	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Average	Standard Dev	Max	Min
Load	80	122	106	96	71	99		106	97	17	122	71
Lift jack	120	65	82	79	85	43		92	81	24	120	43
Tape ends and valve inlets	33	99	114	76	95	50		92	80	29	114	33
Grind lower swage	172	211	261	404	102	342		337	261	107	404	102
Change sides	156	179	141	138	210	109		199	162	36	210	109
Grind upper swage	276	298	174	436	297	491	288	797	382	194	797	174
Air blow	162	149	164	75	159	161	108	71	131	40	164	71
Blow torch and straighten	2021	2096	1123	2139	4198	3374	2535	808	2287	1106	4198	808
Unload	105	140	116	75	82	74		141	105	29	141	74
Total processing time(sec)	**3125**	**3359**	**2281**	**3518**	**5299**	**4743**	***Incomplete data**	**2643**	**3567**	**1090**	**5299**	**2281**
Total processing time(h:mm:ss)	**0:52:05**	**0:55:59**	**0:38:01**	**0:58:38**	**1:28:19**	**1:19:03**	***Incomplete data**	**0:44:03**	**0:59:27**	**0:18:10**	**1:28:19**	**0:38:01**

Specialised Task
General Task

OD Grinding

Steps	Time (sec)	Time (sec)	Time (sec)	Average	Standard Dev	Max	Min
Load	128	349	172	216	117	349	128
Grind	852	1875	1980	1569	623	1980	852
Hand grind	552	1051	706	770	256	1051	552
Unload	188	181	78	149	62	188	78
Documentation	62	69	67	66	4	69	62
Change grinding belt		322		322		322	322
Total processing time(sec)	**1782**	**3847**	**3003**	**2877**	**1038**	**3847**	**1782**
Total processing time(h:mm:ss)	**0:29:42**	**1:04:07**	**0:50:03**	**0:47:57**	**0:17:18**	**1:04:07**	**0:29:42**

Specialised Task
General Task

MPI

Steps	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Average	Standard Dev	Max	Min
Grind ends of mandrel	163	189	85	89	132	52	189	85
Load	122	96	178	114	127	35	178	96
Documentation	15	16	42	77	38	29	77	15
Adjust end contacts	40	30	63	37	43	14	63	30
Close curtains	33	32	52	29	36	10	52	29
Test	752	560	469	392	543	155	752	392
Open curtains	18	55	34	17	31	18	55	17
Demagnetise	177	63	52	80	93	57	177	52
Put on colour tape	14	10		12	12	2	14	10
Unload	189	111	143	124	142	34	189	111
Write serial no. on end of mandrel	28	31		21	27	5	31	21
Total processing time(sec)	**1551**	**1193**	**1118**	**992**	**1214**	**240**	**1551**	**992**
Total processing time(h:mm:ss)	**0:25:51**	**0:19:53**	**0:18:38**	**0:16:32**	**0:20:14**	**0:04:00**	**0:25:51**	**0:16:32**

Specialised Task
General Task

Hardness Test								
Steps	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Average	Standard Dev	Max	Min
Load	87	110	128	77	101	23	128	77
Grind	73	93	67	116	87	22	116	67
Small grinder	54	78	73	61	67	11	78	54
Punch holes	225	258	413	393	322	95	413	225
Scan	89	88	112	67	89	18	112	67
Stamp	27	48	12	14	25	17	48	12
Enter into system	391	341	417	105	313	143	417	105
Put on colour tape	29	32	11	23	24	9	32	11
Unload	92	108	82	24	77	37	108	24
Total processing time(sec)	**1067**	**1156**	**1315**	**880**	**1105**	**181**	**1315**	**880**
Total processing time(h:mm:ss)	**0:17:47**	**0:19:16**	**0:21:55**	**0:14:40**	**0:18:25**	**0:03:01**	**0:21:55**	**0:14:40**

Specialised Task
General Task

Cold Straightening									
Steps	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Time (sec)	Average	Standard Dev	Max	Min
Load	135	128	73	153	67	111	39	153	67
ID drift and adjust mandrel position	149	189	51	97	108	119	53	189	51
Apply pressure	4422	4117	5205	2893	2100	3747	1241	5205	2100
Put on colour tape	21	15	8	10	13	13	5	21	8
Unload	111	164	149	166	114	141	27	166	111
Total processing time(sec)	**4838**	**4613**	**5486**	**3319**	**2402**	**4132**	**1247**	**5486**	**2402**
Total processing time(h:mm:ss)	**1:20:38**	**1:16:53**	**1:31:26**	**0:55:19**	**0:40:02**	**1:08:52**	**0:20:47**	**1:31:26**	**0:40:02**

Specialised Task
General Task

OD Drift	
Steps	Time (sec)
Set up OD bars	1251
Load and test mandrel	546
Unload mandrel onto floor	170
Load mandrel onto trolley	76
Total processing time(sec)	**2043**
Total processing time(h:mm:ss)	**0:34:03**

Specialised Task
General Task

Pressure Test									
Steps	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Time (sec)**	**Average**	**Standard Dev**	**Max**	**Min**
Load onto trolley	120	60	58	83		80	29	120	58
Grind swages	60	60	78	95		73	17	95	60
Oil and grind pocket	60	60	128	102	59	82	32	128	59
Air blow	60	30	25	28	5	30	20	60	5
Push trolly into test bay	60	30	36	47		43	13	60	30
Load on bench & clamp	55	85	52	80	89	72	17	89	52
Redress dummy valve	35	225	18	214	155	129	98	225	18
Install dummy valve	48	25	30	150	32	57	53	150	25
Install plug on upper swage	110	134	90	80	78	98	24	134	78
Fill with water	122	76	70	113	96	95	23	122	70
Install plug on lower swage	110	120	144	108	149	126	19	149	108
Bleed off bubbles	40	40	56	90		57	24	90	40
Test	1077	840	994	1038	701	930	156	1077	701
Remove plugs	143	120	118	158	92	126	25	158	92
Remove dummy valve	40	73	48	80	16	51	26	80	16
Drain water & blow	75	52	66	65	22	56	21	75	22
ID drift	15	22	13	17	20	17	4	22	13
Put on red plugs and blue tape	60	60	45	65	26	51	16	65	26
Apply rust inhibitor on pocket	60	60	38	53	14	45	20	60	14
Unload	120	60	56	40	50	65	32	120	40
Push the trolley out of test bay	35	25	30	48		34	10	48	25
Inspection report (eQ & Monitoring)	45	53	60	47	208	83	70	208	45
Total processing time(sec)	**2550**	**2310**	**2253**	**2801**	**1812**	**2345**	**369**	**2801**	**1812**
Total processing time(h:mm:ss)	**0:42:30**	**0:38:30**	**0:37:33**	**0:46:41**	**0:30:12**	**0:39:05**	**0:06:09**	**0:46:41**	**0:30:12**

Specialised Task
General Task

Appendix II – Spreadsheet calculations of manpower plans

Table II-1: Planned Cycle times of different mandrel types over the years

Planned Cycle Times (min)														
	Year	Projected Demand	No. of Shifts (5 days a week)			No. of Shifts (5.5 day a week)			No. of Shifts (6 day a week)			No. of Shifts (7 days a week)		
			3	2	1	3	2	1	3	2	1	3	2	1
Ovals	2010	2000	101.0	67.3	33.7	112.5	75.0	37.5	124.0	82.6	41.3	146.9	97.9	49.0
	2011	4000	50.5	33.7	16.8	56.2	37.5	18.7	62.0	41.3	20.7	73.5	49.0	24.5
	2012	5000	40.4	26.9	13.5	45.0	30.0	15.0	49.6	33.1	16.5	58.8	39.2	19.6
	2013	6000	33.7	22.4	11.2	37.5	25.0	12.5	41.3	27.5	13.8	49.0	32.6	16.3
Rounds	2010	500	404.1	269.4	134.7	450.0	300.0	150.0	495.8	330.6	165.3	587.6	391.7	195.9
	2011	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
	2012	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
	2013	1000	202.0	134.7	67.3	225.0	150.0	75.0	247.9	165.3	82.6	293.8	195.9	97.9
Total	2010	2500	80.8	53.9	26.9	90.0	60.0	30.0	99.2	66.1	33.1	117.5	78.3	39.2
	2011	5000	40.4	26.9	13.5	45.0	30.0	15.0	49.6	33.1	16.5	58.8	39.2	19.6
	2012	6000	33.7	22.4	11.2	37.5	25.0	12.5	41.3	27.5	13.8	49.0	32.6	16.3
	2013	7000	28.9	19.2	9.6	32.1	21.4	10.7	35.4	23.6	11.8	42.0	28.0	14.0

Table II-2: Calculations of manpower plans

		Cluster 1		Cluster 2			Cluster 3	Cluster 4		Cluster 5			Cluster 6				
		ID Welding (Rounds only)	Fit Up (Rounds only)	Fit Up (Ovals only)	Plasma Cutting (Ovals only)	Pocket Fitting (Ovals only)	Full Welding	Hot Straightening	OD Grinding	Cold Straightening	Heat Treatment	OD Drift	MPI (30% tested)	Hardness Test	Pressure Test		
2010	Work Content (min)	128.5	106.9	40.1	17.4	34.9	425.8	59.4	48.0	68.9	32.0	34.1	7.8	18.4	39.1		
Baseline	PCT	185.7		191.1			121.7	121.7		155.9			68.4				
(6/7 days	No of workers per shift	1		1			4	1		1			1			Total workers	26
a week)	Actual Planned cycle time	185.7		191.1			486.6	121.7		155.9			68.4				
	PCT	182.0	91.0	56.6		37.7	47.7	31.8	47.7	79.5	79.5		28.6		42.9		
	No of workers per shift	1	1	1		1	9	2	1	2	2		1		1	Total workers	56
2011	Actual Planned cycle time	182.0	91.0	56.6		37.7	429.4	63.6		63.6	79.5		28.6		42.9		
	PCT	202.0	67.3	42.1	42.1	14.0	35.4	35.4	23.6	35.4	35.4		70.9				
	No of workers per shift	1	1	1	1	1	12	2	2	2	2		1			Total workers	75
2012	Actual Planned cycle time	202.0	67.3	42.1	42.1	14.0	425.2	118.1		70.9	70.9		70.9				
	PCT	187.5	62.5	37.5	25.0	12.5	31.2	31.2	52.1	72.9	31.2		62.5				
	No of workers per shift	1	1	1	2	1	14	2	1	1	2		1			Total workers	82
2013	Actual Planned cycle time	187.5	62.5	37.5	50.0	12.5	437.5	114.6		72.9	62.5		62.5				