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THROUGHPUT IMPROVEMENT AND REWORK REDUCTION FOR LARGE STRUCTURAL COMPLEX ENGINEERED COMPONENTS

A Thesis in

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by

Kamalesh Singh

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The thesis of Kamalesh Singh was reviewed and approved* by the following:

Robert C. Voigt
Professor of Industrial and Manufacturing Engineering
Thesis Co-Advisor

Paul C. Lynch
Instructor of Industrial and Manufacturing Engineering
Thesis Co-Advisor

Paul Griffin
Peter and Angela Dal Pezzo Department Head Chair
Department of Industrial and Manufacturing Engineering

*Signatures are on file in the Graduate School.

ABSTRACT

This thesis focuses on the data driven analysis for the complexity involved in the complex, and highly engineered and large component manufacturing. The objective of this research project is to form the first base for the analysis for such large component manufacturing, to identify the improvement opportunities and to provide recommendations to increase the throughput and to reduce the manufacturing lead time. The BEST 18/10 SBOP lower housing had the lowest processing time and non value added times as compared to the TYPICAL and WORST ones. Rework played the major role in increasing the processing time and non value added times like movement times, queue and hold times due to the increase in number of rework operations. The BEST 18/10 SBOP lower housing followed the standard router very closely and had the least Work In Process (WIP) where as TYPICAL and WORST 18/10 SBOP lower housings had the large deviations from the standard router and had higher WIP numbers which eventually cost the company in repair cost, more delays, affected supply chain and more shop floor space to be allocated for the storage of the rework parts.

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I dedicate my thesis to my parents.

Thank you.

Chapter 1

Introduction

Today highly competitive markets due to increasing globalization, growing product range diversity, and rising consumer awareness, are forcing supply chains to adapt constantly to different stimuli. Increased competition among various players is also pointing towards overall supply chain performance over the performance goals of individual players. Of key importance is, supply chain (SC) cost and responsiveness. Responsiveness here is the ability of the supply chain to respond quickly to changing customer needs, preferences, and options through reduced supply chain cycle time rather than the higher service levels achievable through increased distribution of channel inventory (Vanteddu et.al. 2007).

Cycle time is one of the key parameter affecting the overall supply chain that can lead to faster development of the product and vice versa. However, faster development cycles alone may not be enough to achieve higher performance. Faster development cycles along with certain organizational practices such as the use of cross-functional teams and the use of advanced design tools, are associated with higher performance. Company performance in order to meet the customer demand can be seen as a function of the interaction between cycle time and organizational practices. Some practices act as "enablers" that enhance the benefits from cycle time reductions, and others acting as "suppressors" that reduce the potential gains (Ittner et.al. 1997).

All of these efforts of faster development at lower cost get overshadowed if rework comes in to the picture. The scheduling of the new items and the defective items of the same product manufactured at the same facility becomes very complex. The rework is caused by many factors including unstable production environments, non-perfect technology or human mistakes. However in many cases, instead of disposing the rework items, these items are put into recovery processes in order to regain material and value added (Inderfurth et.al. 2007). Having said that, it is always important to improve the process in order to reduce the chances for rework and it is advisable to perform the root cause analysis and act on them.

1.1 Research Objectives and Expected Contributions

This thesis is an attempt to carry out a data driven analysis to study the complex nature of complex, highly engineered, large component manufacturing such as Spherical Blowout Preventers (SBOPs). The goals for this study are:

- To study the complexity involved in the large component manufacturing and if possible provide the recommendations for increasing the throughput for lower housing manufacturing.
- To quantify the role of rework in affecting the production Cycle Time, Job Order Closure Variance (JOCV) and Work In Process (WIP).
- To find the root causes and provide the base recommendations for process delay, severe rework and low machine utilization.

The results of this study offer a valuable insight in identifying improvement opportunities and provide the base for detailed analysis in the future. The results have been analyzed and base level recommendations have been provided for increasing throughput and cycle time reduction. Furthermore, the results from the root cause analysis can be explored in detail to plan action items in order to tackle these problems. However, a comprehensive analysis is out of the scope of the present study.

1.2 Thesis Overview

Chapter 2 provides a brief review of the literature most relevant to this study. Chapter 3 describes the company's profile along with the manufactured product chosen for doing the analysis. Another section in this chapter describes the present process followed in the manufacturing of that product. Finally supply chain and scheduling involved in procurement of the raw material, outside vendor operations and their lead times are discussed.

Chapter 4 details the problem statement and improvement opportunities identified in the study. It also talks about the types of SBOPs with their manufacturing cost and future order structures. This chapter also outlines the criteria for the selection of 18 in. SBOP as the product for this analysis.

Next, Chapter 5 discusses the sources of the data for the analysis. The two sources described are GLOVIA and KRONOS company databases along with their short descriptions. A part sampling of data is described in this chapter in order to understand the terminologies and attributes of the data. The chapter also highlights the assumptions that were made to simplify the analysis and the data scrubbing techniques that were used.

The results for the study are provided in Chapter 6. The first result describes the cycle time analyses for BEST, TYPICAL and WORST 18/10 SBOP lower housings at three different levels of fidelity; activity based, work center based and operations based analyses. The next section of this chapter illustrates the results from WIP analysis for the above mentioned parts. The throughput analysis results along with root cause analysis for some frequent rework problems and cost justification for some major Non Conformance Report (NCR) codes have also been discussed.

Chapter 7 concludes this thesis. The chapter begins with a discussion of the results presented in Chapter 6. A description of future work that may be done in this field is also discussed in this chapter.

Chapter 2

Literature Review

2.1 Manufacturing Strategy

In today's market, the technological and competition forces are changing very rapidly. In order to cope with these factors, radical changes in organizations must occur. The survival of a firm is largely dependent on its ability to respond to customer requirements as quickly as possible while also becoming leaner. Outsourcing is becoming one of the main strategies as it is increasingly more difficult and less economical for companies to meet their own needs in house (Gunasekaran et.al. 2001).

The rise in interest in manufacturing strategies is the natural reaction to the continued turbulence in the operating environment of most manufacturing firms. The degree of competitive priorities varies from firm to firm which defines their manufacturing capabilities. The competitive priorities for a firm are quality, on time delivery, cost, flexibility, degree of innovation and return on assets (Corbett et. al. 2002).

2.2 Manufacturing Planning, Supply Chain and Performance Indicators

The knowledge about the products and processes is a must for manufacturing companies to be competitive in the market and this becomes even more important when the complexity of the product increases. Also, increases in choice and therefore more involved decision making increase the complexity of design and manufacturing, posing new challenges in selecting the process and manufacturing planning (Balogun et. al. 2004). Organizational capabilities are based on this knowledge. Capabilities combine to become competencies which become the key domain where the organization excels. Therefore, organizations that seek to improve their capabilities need to identify and manage their knowledge assets (Marr et. al. 2004).

To cope with the challenge of decision making and manufacturing planning, the integration of all entities of the overall supply chain for large, complex product manufacturing is necessary. The actual goal for effective supply chain management is to obtain a good integration of all intelligent agents in order to make each local strategy as cooperative as possible. The knowledge assets play a vital role in decision making and designing the supply chain. The supply chain should be robust enough to connect material suppliers, producers, distributors and customers for every manufacturing and distribution step, from raw material procurement to final product delivery (Lu et. al. 2008).

The performance of the supply chain and knowledge assets must be measured to evaluate the organization in order to communicate its real value to the market. In addition, these metrics should be measured to identify the knowledge components of the organization in order to manage them for continuous performance improvement (Marr et. al. 2004). The performance measurement is being done by Performance Indicators or Key Performance Indicators (KPI). KPIs reflect and derive from the organizational goals. The goals are being set by the organization to get the job done that needs to be done within the resources available (Shahin et. al. 2006).

2.3 Cost of Quality and Rework

Implementation of excellent manufacturing strategies and efficient process plans in an organization is always recommended to efficiently produce products. However, products and production processes are always subject to a certain level of variation. Increased variability can lead to a higher cost of quality and thus organizations must understand the concept of variation in order to implement process improvement initiatives to decrease variability (Dhafr et. al. 2006). Cost of Quality is defined as the cost of not creating quality products or services.

In an organization, some of the manufactured products can be defective or require rework due to the variability caused by the manufacturing process, environment, or human mistakes. The rework is done with an aim to recover the defective products in such a way that they meet the quality level of a good item. However, the part being reworked is rejected if the cost of quality exceeds its value. Rework affects the overall supply chain as the planning for the reworked parts along with the new parts on the same machine becomes very challenging and cumbersome (Inderfurth et. al. 2007).

2.4 Summary

As discussed in previous sections, manufacturing firms need to adapt as quickly as possible with the rapidly changing technologies and customer requirements without failing to meet the on-time delivery of the quality product to stay afloat in the market. However, as the complexity of the product increases, the decision making related to the manufacturing of the complex product becomes more challenging. The decision making gets even more tough and cumbersome when rework becomes an issue during production. Rework negatively impacts KPIs such as cycle time, throughput, on time delivery and utilization of machines along with increasing WIP during production. Sections 2.2 and 2.3 provide the idea of the added issues due to increased complexity of the product and the rework involved. This thesis is an attempt to quantify these issues by developing a data driven analysis.

Chapter 3

Product and Process Description

3.1 Company's Profile

Company X is a worldwide leader in providing major mechanical components for land and offshore drilling rigs, complete land drilling and well servicing rigs, tubular inspection and internal tubular coatings, drill string equipment, extensive lifting and handling equipment, and a broad offering of down-hole drilling motors, bits and tools. It also provides supply chain services through its network of distribution service centers located near major drilling and production activity worldwide.

3.2 Product Overview

A blowout preventer is a large, specialized valve used to seal, control and monitor oil and gas wells. Blowout preventers were developed to cope with extreme erratic pressures and uncontrolled flow emanating from a well reservoir during drilling. Company X produces SBOPs with 18 in. SBOP being the largest and most widely used for ocean floor wells, Figure 3.1.

Fig. 3.1: Typical Spherical Blowout Preventer. An 18 in. SBOP weighs approximately 62,000 lbs

There are two other types of blowout preventers that are being used by oil companies, namely ram blowout preventers and annular blowout preventers. However, SBOPs have the following important advantages over the other types of blowout preventers:

- SBOP consist of only five major parts – the upper housing, the lower housing, the sealing element, an adapter ring, and a piston. This simple design provides a rugged, reliable preventer and ease of service in the field.
- SBOPs have a simple hydraulic system with only two hydraulic connections, one for opening and one for closing.
- SBOPs are generally 15 – 20% shorter than comparable annular preventers which is an added advantage when installation space is limited.

Company X processes only one of the major components of the 18 in. SBOP which is the Lower Housing and relies completely on outside vendors for on time delivery for rest of the components like Adaptor Rings, Locking Rings, Upper Housings and Pistons. The final SBOP assemblies are supplied to either Stack Pads as part of an assembled deep sea stack or directly to the external customers.

3.3 Process Description

3.3.1 Materials, Supply Chain and Scheduling

Each large SBOP unit consists of five major parts - the lower housing, upper housing, piston, adapter ring, and sealing ring. The lower housing being the heaviest and complex of all the components, its processing is done in-house while the manufacturing of the other parts is outsourced. The raw materials for a lower housing are three closed die forgings - a lower ring, a middle ring and an upper ring, supplied in the heat treated condition. Due to forging capacity constraints, the raw materials are supplied in the form of three separate forged rings which are welded together and machined to form a single lower housing.

Once an order is received, a planner sets the due date for forging delivery in such a way that 16 weeks of lead time are used to release the purchase order (PO) to vendor for raw materials and procure them, at least 4 weeks of buffer before the due date, and production lead time for the actual production which can range from 10-12 weeks. An additional lead time buffer of 4 weeks is planned to accommodate any rework or delay in the manufacturing process. The production time includes the processing of lower housing, the procurement of all other supporting components of SBOP, their assembly, testing, washing and painting. Figure 3.2 shows company X's typical planning for SBOP manufacturing.

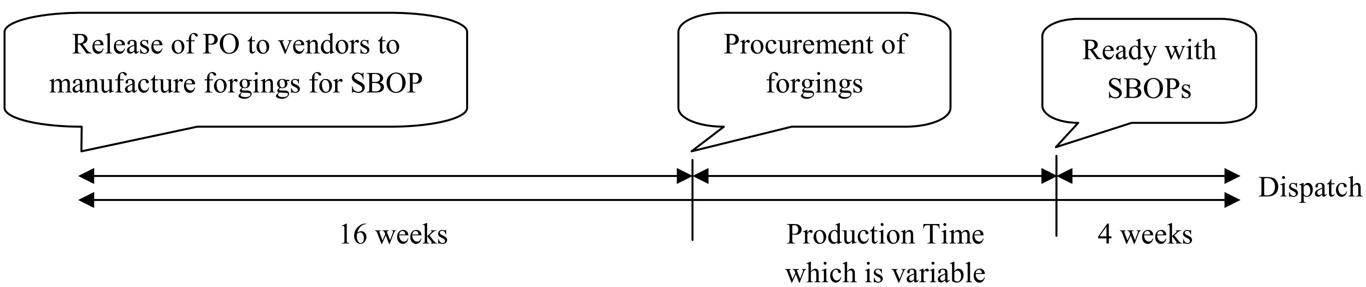

Fig. 3.2: Typical planning for SBOP manufacturing

After the forgings are received, SBOP planner issues three different Work Orders (WO), one for each ring, to start the manufacturing of lower housing and consults the production scheduler for the rough machining of these forgings for welding preparation. If the in-house capacity has enough room to accommodate the processing of these forgings then further scheduling is done or else these forgings are sent out to vendors for the rough machining job. The weld – prepped forgings are sent back to company X's welding area for initial inspection prior to welding and stress relieving. If the part fails an inspection, it is sent back for vendor or internal rework which adds additional weeks to the processing. Re-work is common and poses one of the most difficult scheduling challenges. To minimize the re-work involved in weld related activities, procurement of lower housing forging in a single piece which will eliminate the major welding step of joining the three rings together. Once the roughing operation is done, the planner issues another work order called finish machining to coordinate all the operations post rough machining.


Raw Material


Weld Prepped – Upper Ring


Weld Prepped – Middle Ring


Weld Prepped – Lower Ring


Weld Assembly


Sub Arc Welding Process


Stress Relieving


Finish Machining


Final SBOP Assembly

Fig. 3.3: Major steps involved in SBOP manufacturing

The rough machining and finish machining for the lower housing is planned on the machining centers listed below by the help of machine scheduler:

- **Machine No. 416:** Milling on flange areas of the lower housing + turning operation (ID/OD) for welded lower housing + drilling on the flange area
- **Machine No. 418:** Generally used for machining of the body, but if Machine 416 goes down then Machine 418 is used for other turning operations
- **Machine No. 462:** Turning operations for lower and upper housings
- **Machine No. 312:** Milling operations for lower housings
- **Machine No. 306:** Milling operations for lower housings
- **Machine No. 409:** Turning operations for lower housings
- **Machine No. 454:** Dedicated for weld preparation

The scheduling of the above machining centers is driven by their availability. For the secondary machining operations such as turning on machines 416, 462 and 409 and milling on machines 312 and 306, the scheduler allocates the forging to the machine that has shortest machining queue.

3.3.2 Manufacturing

The SBOP product line has 7 machining centers, 4 welding stations and 4 stress relieving stations. Each machining center is dedicated to perform a particular operation (as described previously). The major operations performed in SBOP line are rough machining, stress relieving, welding, finish machining, inspection and assembly. A preliminary manufacturing process map for the SBOP product line is displayed in Figure 3.4.

The overall process starts with the heat treated forgings being received at the company’s yard. The forgings are then either transported to the machining area (machine no. 454) via forklift for the initial rough machining or are sent out to vendors if the capacity for 454 doesn’t allow performing the rough machining operation in-house. After the rough machining, the forgings are sent to the welding area where the forgings are staged for initial inspection. If the forgings pass initial visual inspection, the process continues and forgings are sent for the next operation which is welding, otherwise the forgings are marked and sent back to rework.

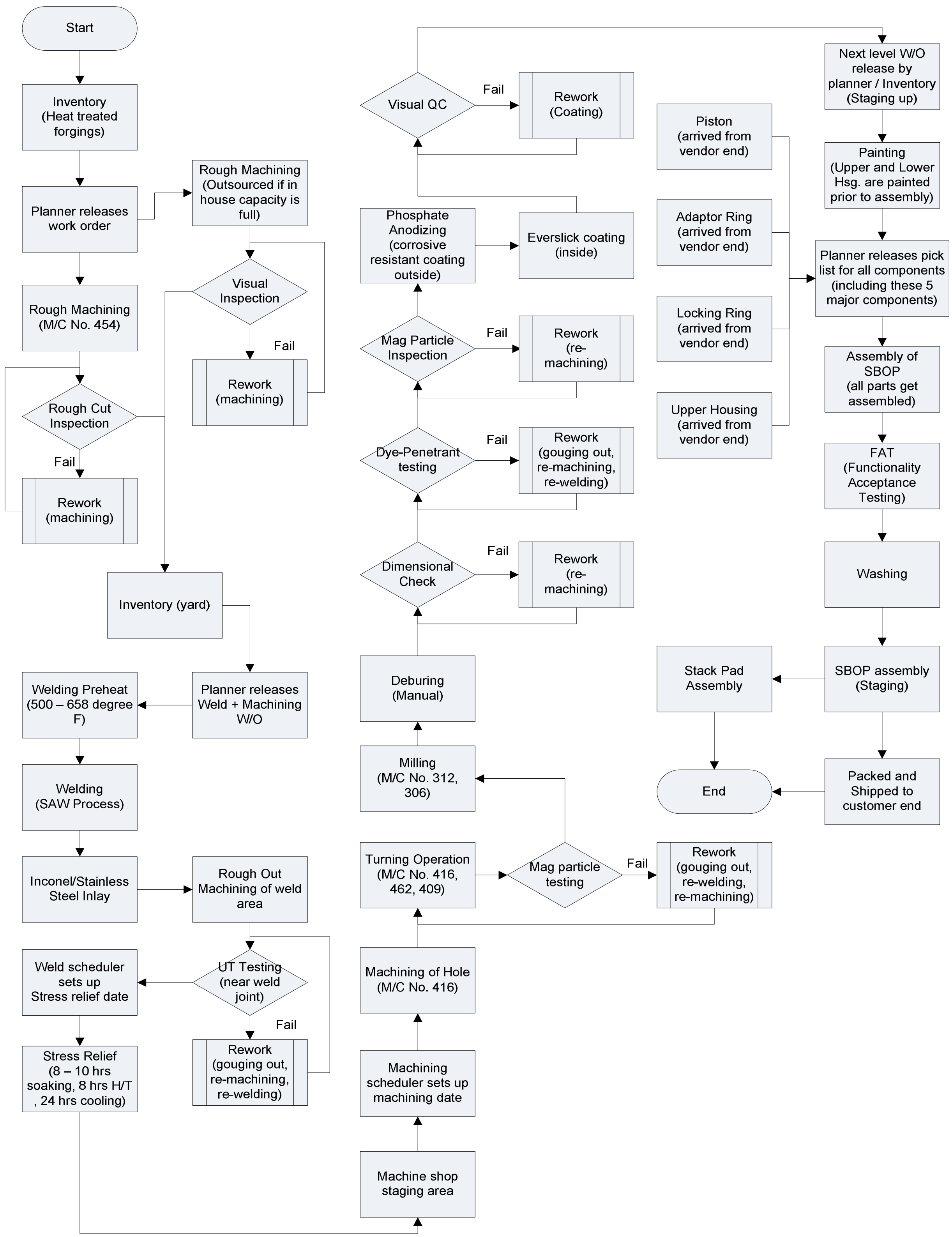

Fig. 3.4: SBOP Process Flow Chart

For the welding operation, the operator sets up the rough machined parts on a turn table which rotates at a speed of 20 – 35 inch/min. The overall time for welding is approximately 30 hrs and includes operations such as centering of rough machined parts, welding of back-up bars on the side, and rotating the table by 90^0. The whole lower housing pre-assembly is then preheated to 500^0F – 658^0F for 1 – 3 hrs. After preheat, submerge arc welding (SAW) is used in multiple passes to weld the parts together. After welding, Inconel/Stainless Steel is inlaid to the ring groove of the flange which is the sealing area (this prolongs the life of flange/outlet) and sometimes on the side as well. The complete welding process (including set up time + welding + Inconel/Stainless Steel inlay) takes around 250 hrs. After inlay, the main weld seams are rough machined manually prior to ultrasonic testing to identify sub-surface welding defects. If the parts pass the inspection, the process continues and the parts are sent for the next operation which is stress relieving, otherwise the parts are marked and sent back for rework at the welding station.

For the stress relieving operation, the parts are moved to the stress-oven area from the welding area, and the weld shop scheduler schedules them for the final stress relieving. The total stress relief cycle is 8 – 10 hrs of soaking, 8 hrs of tempering at 1175^0F ± 25^0F and then 24 hrs of cooling partially inside the furnace and partially outside. The stress relieving time depends on the thickness of weld (1 hr/inch). After the final stress relieving operation, a machine scheduler schedules the parts on machine 416 for initial milling operation of the flange area, the ring groove on the flange, turning operations on neck area, and drilling operation (all in one machining set up). Later, the part is flipped over and is sent for inner bore turning operations on one of these machines 416, 462 and 409 depending on the shortest machining queue. After the turning operation, part undergoes a series of tests – dimensional checks, dye-penetrant testing of ring groove area and magnetic particle inspection. If the parts fail any of these tests, they are sent back for the rework, otherwise they move for the next process which is a series of milling operations.

After the milling operations, the parts are sent out for final quality check – hardness testing, dimensional checks, magnetic particle testing, ultrasonic testing and dye-penetrant test. If the parts fail any of these tests, they are sent back for the rework, otherwise they move for the next process which is a coating operation. For the coating operation, the parts are sent for a corrosion resistant phosphate coating on the outside surface and Everslick coating on the inside. Later, the lower housing and upper housing are painted before they are sent to the assembly area where other large SBOP components such as pistons, adapter rings, locking rings and upper housings are assembled together. A completed SBOP assembly is then moved to a test bay where it undergoes testing such as pressure testing at pressures as high as 15000 psi, hydraulic testing, and well bore testing. All of these tests check the complete functionality of the SBOP and certify the SBOP as per API (American Petroleum Institute) standards. After testing, the SBOPs are sent for washing and painting and from there they are sent out to either stack pad assembly or directly to a customer.

Chapter 4

Problem Statement

4.1 Improvement Opportunities

The large bore SBOP product line faces an urgent need to increase throughputs level and reduce lead times. However, due to the complexity of the SBOP and the lack of key system performance measures the best strategies to reach system performance goals are not clear.

The key areas of improvement for the large SBOP product line include:

- Lead Time Reduction
- Throughput Enhancement
- Overall Efficiency Improvement
- Rework Reduction
- Non-value Added Time Reduction

Preliminary discussion with company X staff suggests that current limitations include excessive rework, poor machine utilization, and poor supplier reliability and on-time delivery. Increasing the throughput of the large SBOP line with increases in machine utilization and lead time reduction will help in meeting customer demands by clearing backlogs and will result in cost saving which will add to the bottom line.

In addition to the above argument, company X is also expecting a sharp increase in future orders for SBOPs. However, as explained earlier that present capacity and throughput restricts the planner to the manufacturing of 4 units of SBOP/month. Therefore orders for any extra units must be manufactured by outside vendors (OSV) which reduces the profitability significantly. Thus, any throughput and capacity improvement will help company X to process more and more orders in-house and increase its revenue.

Figure 4.1 shows the revenue comparison among various SBOPs. The revenue generated by the large bore SBOPs (13/10 and above) is 60% of the total SBOP business. Also, among all large bore SBOPs, 18/10 SBOP accounts for 63% of the business, figure 4.2. These reasons provide us the strong motivation to start with 18/10 SBOP line to increase throughput and capacity.

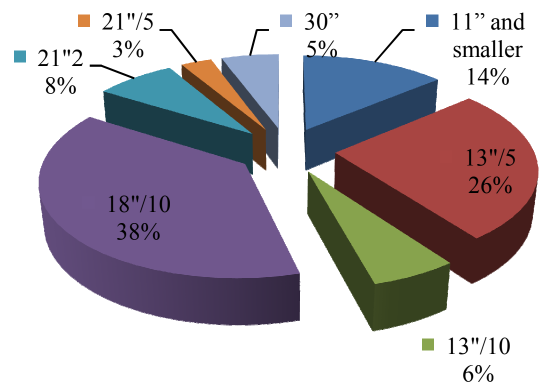

Fig. 4.1: Pie chart for the revenue comparison between different types of SBOPs

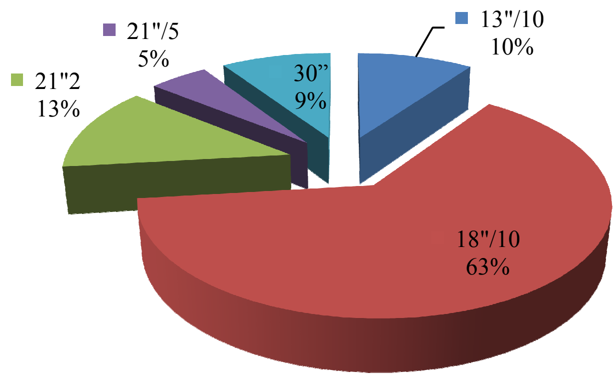

Fig. 4.2: Pie chart showing the revenue comparison between various large bore SBOPs

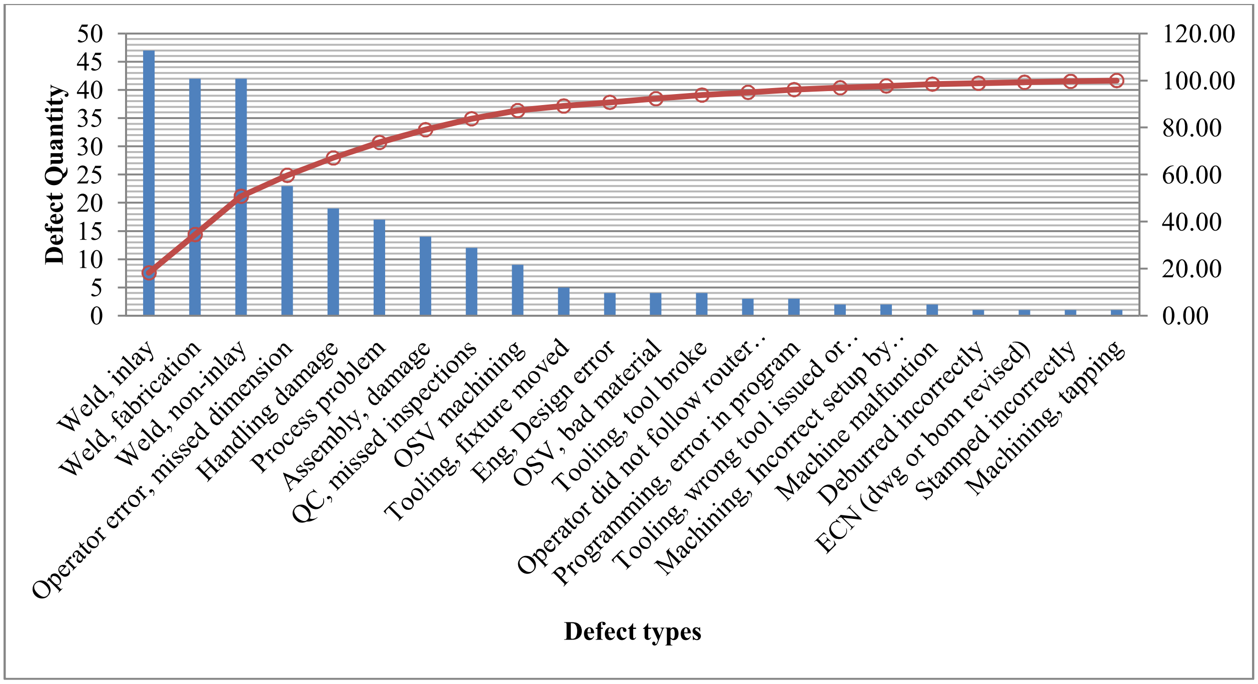

Fig. 4.3: NCR analysis for SBOP line (based on 2011 data)

A Pareto analysis of current NCRs from January 2011 to date is displayed in Figure 4.3 for 18/10 SBOP manufacturing. The most common defects are welding related and operator errors (missed dimensions). This analysis suggests that the four major types of defects account for almost 60% of the total defects in the 18/10 SBOP manufacturing. Controlling these major defects will reduce the amount of rework and increase throughput.

4.2 Analysis Background

Section 4.1 advocates for 18/10 SBOP as the focus of study to reduce the cycle time and increase its throughput. However, as explained in Chapter 3, company X only manufactures lower housings for the 18/10 SBOPs. The rest of its components are being outsourced. Thus the focus of the analysis will be completely on18/10 SBOP lower housing manufacturing by studying cycle time, throughput scenarios and NCR reduction.

Data for 29 work orders for 18/10 SBOP lower housings have been provided to carry out the analysis. However, it was very difficult to analyze each and every work order as all of them have different processing times and amounts of rework. Thus to simplify the analysis and to make generic recommendations based on the study, three work orders(parts) were selected for detailed study depending on their total processing time (in days), total number of operations involved and amount of rework. These parts are termed as BEST, TYPICAL and WORST production components with the following description:

- BEST: Lowest processing time, lowest number of operations, no rework
- WORST: Longest processing time, highest number of operations, highest rework
- TYPICAL: Centered in between BEST and WORST

These three parts covered the entire range of variability required for the analysis. Manufacturing strategies based on the analysis of these parts can be applied to future production.

Chapter 5

Data Description

The data evaluated came from the company's ERP system called GLOVIA and its time management software called KRONOS. The data consists of the detailed description of work orders (WO), work order items (WO Item), operations (Oper), machine numbers (Mach), work centers (WC), work center queue (WC Queue) information, actual production times (Act Run), actual setup time (Act SU), transactions dates (First Trx, Last Trx), issue, release and manufacturing close dates for the various operations performed in the shop floor during lower housing manufacturing. Each work order item corresponds to a custom SBOP design depending on the order from the customer(s). The operation number distinguishes different manufacturing operations to process lower housings with standard operations denoted by the numbers correspond to multiples of one hundred and the rework operations with the rest of the numbers. Machine number defines the machine performing the corresponding operations while the work center is the functional step in the manufacturing process. Run time and set up time are the processing times for the particular operation while first and last transaction dates are the start and finish of that particular operation. The issue date, release date and manufacturing date correspond to the issue of the work order, the release of the raw materials and the closing of manufacturing.

Table 5.1: Table showing a sample of the database entrees for production operations for a Work Order (WO)

WO	Item	Description	Oper.	Mach	WC	WC Queue	Act Run	Act SU	First Trx	Last Trx	Issue Date	Release	Mfg. Close
3148183	156113	HSG, LWR, FM, 18-10M SBOP	100	PULMTL	PULMAT	1	0	0			4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	200		QC2	1	0	0			4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	300	200904	WELDSUB	2	148.85	8.95	7/26/10	8/4/10	4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	400		QC2	1	0	0			4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	500	200904	WELDSUB	2	9.17	0	7/29/10	7/29/10	4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	600		QC2	1	0	0			4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	700	200900	WELDSUB	2	7.47	2.65	7/20/10	7/21/10	4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	800	200950	HTSR	3	3.08	0	8/5/10	8/5/10	4/22/10	4/22/10	8/11/11
3148183	156113	HSG, LWR, FM, 18-10M SBOP	900	200950	HTSR	3	3.09	0	8/5/10	8/5/10	4/22/10	4/22/10	8/11/11

Another data set evaluated was the rework data which contained the detailed description of rework operations carried out during lower housing manufacturing. The reporting gives the details about any rework in terms of rework number (NCR#), rework code (RC), rework description (RC Description), its inspection date, work order information (WO), actual setup and run time (Act Setup, Act Run) involved in the rework, total lead time for that rework (Rework LT), and the transaction dates for the start and finish of the rework (First Trx, Last Trx). A sample set of rework data set is shown in the Table 5.2.

A single work order can have multiple rework operations performed during the course of manufacturing. For each rework a unique NCR# coupled with a RC code describing the type of rework is provided. However two different NCR's can have same RC code since a lower housing can undergo same type of rework (RC code) but at different phases of manufacturing. Various RC codes and rework descriptions associated with them are shown in the Table 5.3.

Table 5.2: Table showing a portion of the rework data

NCR#	RC	RC Description	Insp. Date	Insp. Qty.	WO	Act Run	Act Setup	Rework LT	First Trx.	Last Trx.
74202	25	OSV, machining	1/12/2011	1	3148183	37.95001	2.98333	5	1/19/2011	1/24/2011
74202	25	OSV, machining	1/12/2011	1	3148183	4.19167	0	0	1/25/2011	1/25/2011
74281	18	Tooling, wrong tool issued or tool set wrong	1/23/2011	1	3167821	1.01667	0	0	1/26/2011	1/26/2011
74285	8	Weld, inlay	1/24/2011	1	3163113	3.11667	0	21	1/4/2011	1/25/2011
74285	8	Weld, inlay	1/24/2011	1	3163113	34	5.81667	11	2/1/2011	2/12/2011
74293	42	Weld, fabrication	1/27/2011	1	3136076	24.94166	0	157	2/14/2011	7/21/2011

Table 5.3: Table showing various RC codes and their descriptions

RC Codes	RC Description
1	Machining, Tapping
2	Process Problem
6	Stamped Incorrectly
8	Weld Inlay
9	OSV, Bad Material
11	Deburred Incorrectly
18	Tooling, wrong tool issued or tool set wrong
21	Programming, error in program
25	OSV, Machining
29	Machining, Incorrect setup by operator
34	Machine Malfunction
36	Operator did not follow the router instructions
39	Operator error, missed dimension
41	Weld, Non Inlay
42	Weld, Fabrication
43	Handling Damage
48	Assembly, Damage
64	QC, Missed Inspections
69	ECN (DWG or BOM revised)
73	Eng., Design Error
86	Tooling, Fixture Moved
87	Tooling Broke

5.1 GLOVIA

To remain competitive, the manufacturers should be able to introduce and improve products, while continuing to reduce costs. GLOVIA management software helps to define and manage products and allow manufacturers to respond to the customers, while minimizing the disruption to downstream processes. It provides a centralized repository for all product-related data to help speed new product development, compress time-to-market, reduce development costs and manage large product portfolios. It also provides for better visibility, flexibility and control to make manufacturers highly responsive, integrated and lean. Figure 5.1 shows the essential functions of GLOVIA as it is used by company X.

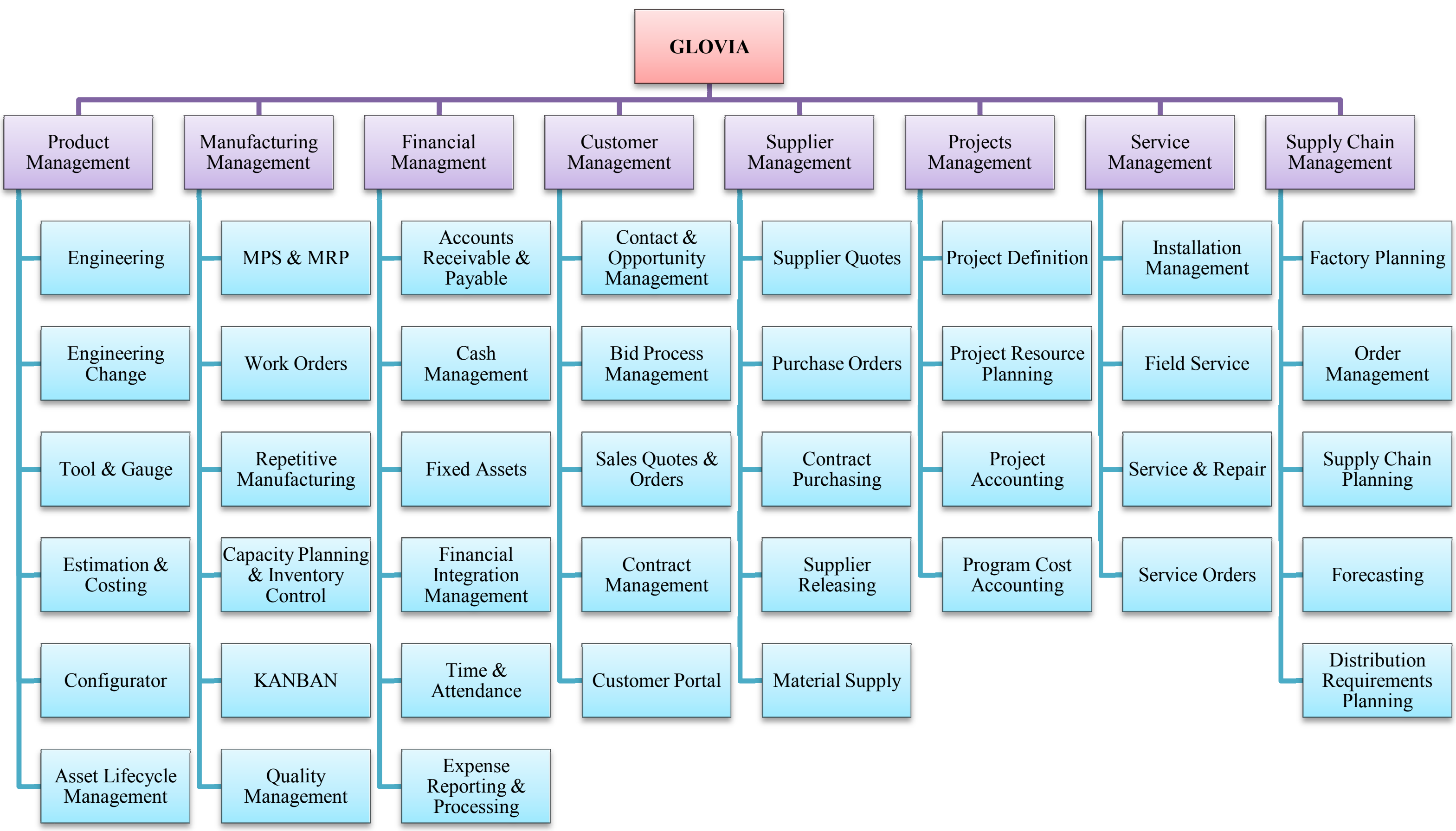

Figure 5.1: The key verticals of the ERP system GLOVIA

5.2 KRONOS

KRONOS is the global workforce management solution to record employee time and attendance transactions, workforce scheduling, and managing employee absence. It helps the firm to control labor costs, minimize compliance risk, and improve the workforce productivity. It also keeps the record of clock-in and clock-out of the employees while performing any operation and thus provides the base to calculate the operational time and eventually the cycle time for the whole production process.

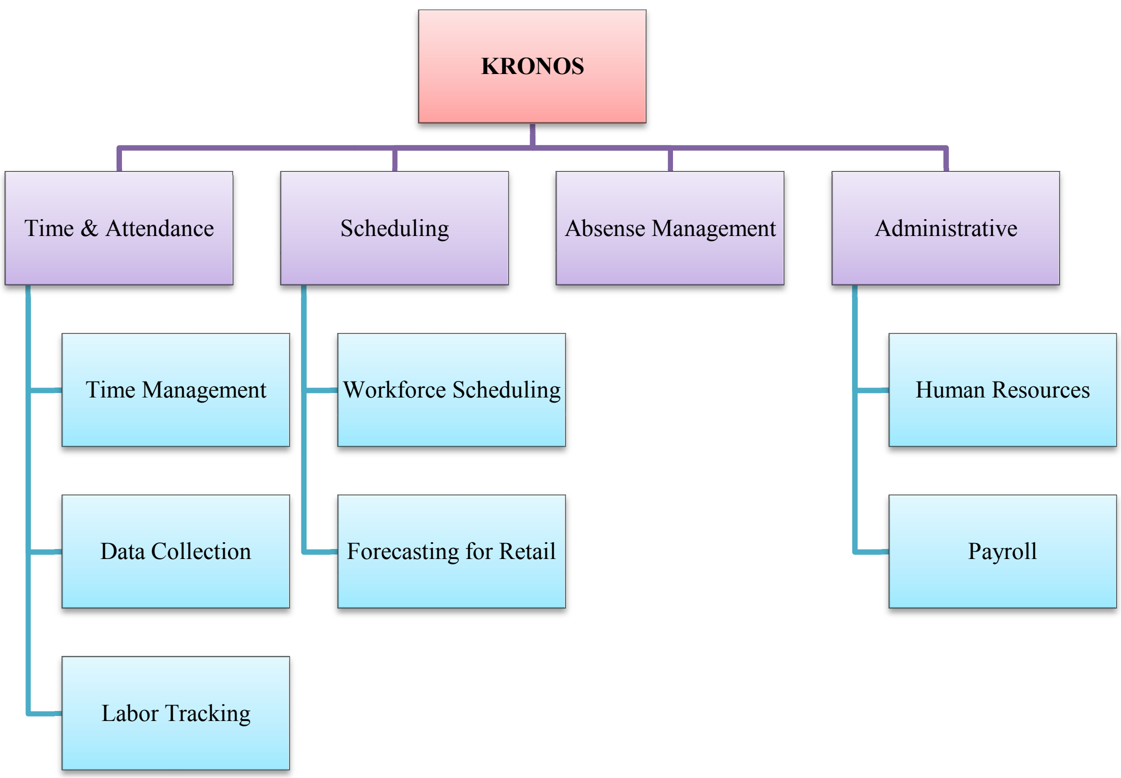

Figure 5.2: Key verticals of the KRONOS management system

5.3 Analysis Assumptions

To set the foundation for the analysis, the following production flow assumptions were made:

- The time associated while moving parts from one work station to another is called the movement time. Since company X management systems do not track the movement times, we have assumed a standard movement time of 10hrs/movement based on the standard router movement time assumption.
- Similarly, the times associated with inspection at different stages of manufacturing are also assumed to be 10hrs/inspection based on the standard router times.
- All calculations are based on average number of work hours/day of 22.86 hrs/day as calculated in Table 5.4:

Table 5.4: Calculation for average number of work hours available per week

Type of Shop	**Mon - Fri (2 shifts)**	**Sat (2 shifts)**	**Sun (2 shifts)**	**Total hrs**
Machine Shop	12hrs/shift	12hrs/shift	12hrs/shift	168
Weld Shop	12hrs/shift	8hrs/shift	8hrs/shift	152
		Average no. of hrs per week		160
		Average no. of hrs per day		22.86

5.4 Data Scrubbing

Data scrubbing is the process of detecting and correcting (or removing) inaccurate records from a data set to make it consistent with other similar data sets in the system. A total of less than 1% of the database data points were adjusted by filling in missing critical data or by removing erroneous entries. The addition or removal of any data set doesn't affect the results of the analysis since the added data points were derived directly from the existing data. Table 5.5

illustrates a data sampling with added data points (enclosed in the blue box) in the data set for the analysis.

Table 5.5: Sample data selection showing added data points

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Work Center	Machine	Operations	Total Time(in Hrs)			NCR #	RC CODES	RC Desc	First Trx	Last Trx	Issue Date	Manu. Close	Hold Time	Queue Time	Timeline
			Act Run	Act Setup	Move Time										
PULMAT	PULMTL	P(50)	0	0							1/6/11				
MOVE					10										
BLAST	905	P(60)	5.12	0					2/1/11	2/1/11			15.72	531.84	26
QC2		P(100)	10	0											
MOVE					10										
WELDMAN	850	P(150)	0	0											
WELDSUB	904	P(200)	56.42	13.67					2/7/11	2/13/11			75.93	0.00	32

Chapter 6

Results

The motivation behind this study is to find the root cause of the 18/10 SBOP lower housing production including late delivery, excessive rework, low machine utilization, and low throughput. The study starts with an activity-based detailed cycle time analysis for the best, typical and worst parts from a simple to complex perspective. The simple analysis includes a breakdown of the overall cycle time based on the activities such as processing time and non-processing time. The complex analysis includes a breakdown of cycle time into the following activities:

Standard Processing: Run time, Move time, Hold time and Queue time

Rework: Run time, Move time, Hold time and Queue time

However, the complex activity based analysis was not sufficient to find the root cause and delays at different work stations, thus two more levels of analysis were performed: work center based cycle time analysis and operations based cycle time analysis.

A work flow and Work in Process (WIP) analysis for best, typical and worst parts which was performed followed by throughput analysis for different machines including the bottleneck machine. Since the bottleneck machine drives the overall throughput of the shop floor, it is important to study it and to evaluate the scope of possible improvements. All these analyses are then followed by the root cause analysis for the process delays and for the top four NCR reasons. Finally, a rework costing analysis has been done to quantify the labor cost involved in the rework to show how rework can affect the revenue generation for the company. Figure 6.1 summarizes the analyses performed. Conclusions based on the analyses are described in the next chapter.

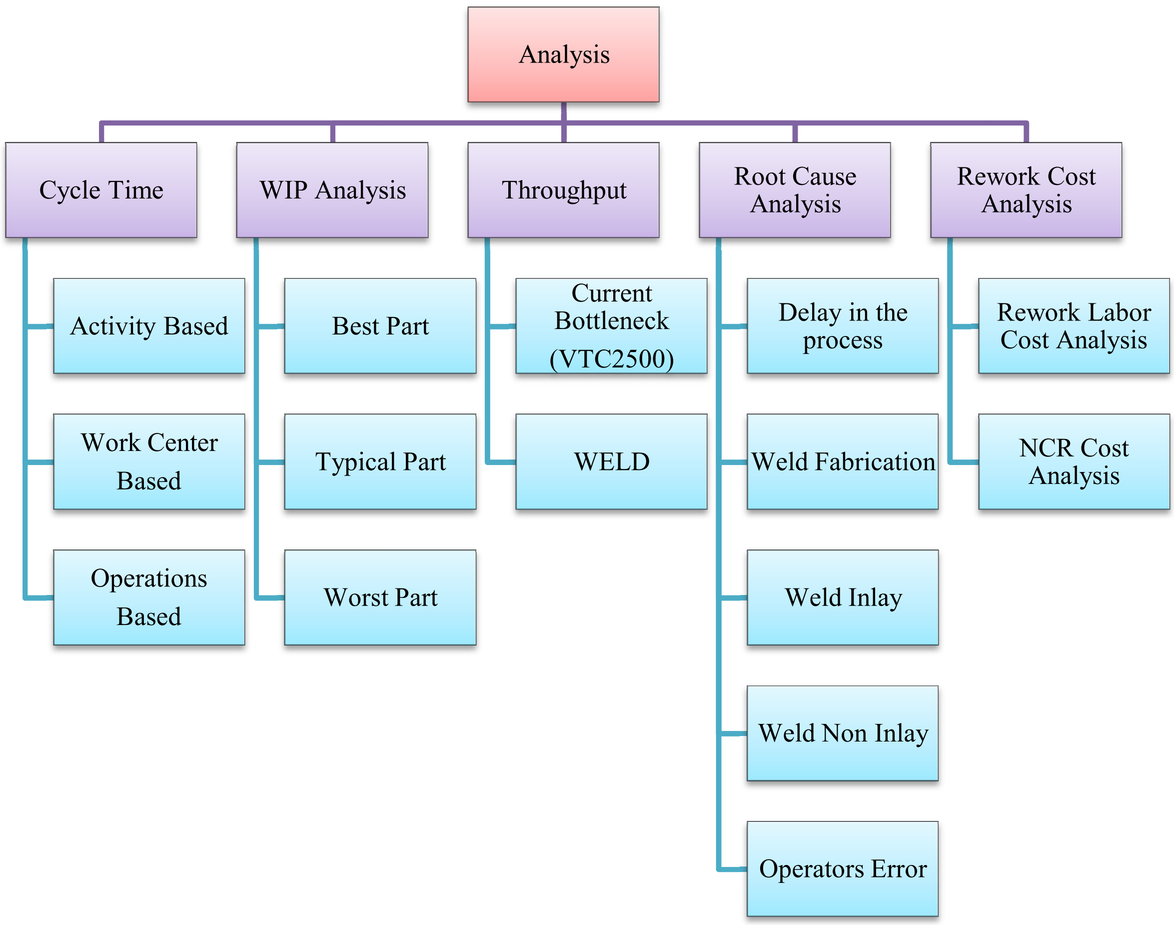

Fig. 6.1: Summary of analyses performed

6.1 Cycle Time

The cycle time is defined as the total elapsed time a part takes to process from the beginning of the manufacturing to the end of the manufacturing. It includes process time during which a unit is acted upon to bring it closer to an output and delay time during which a unit of work is spent waiting to take the next action. In our analysis, we have defined three levels of cycle time analysis: Activity based cycle time analysis, work center based cycle time analysis and operations based cycle time analysis.

6.1.1 Activity Based Cycle Time Analysis

Activity based cycle time distribution is simplest global analysis of the overall cycle time which consists of two major components: processing time (PRT) and non-processing time (Non-PRT). Processing time is the total time for which the part has undergone any form of change directly or indirectly (setup + run times). Rework time (normally considered processing time by GLOVIA) is considered Non-PRT in this analysis. Holding, movement and queue times during the processing are also considered as Non-PRT.

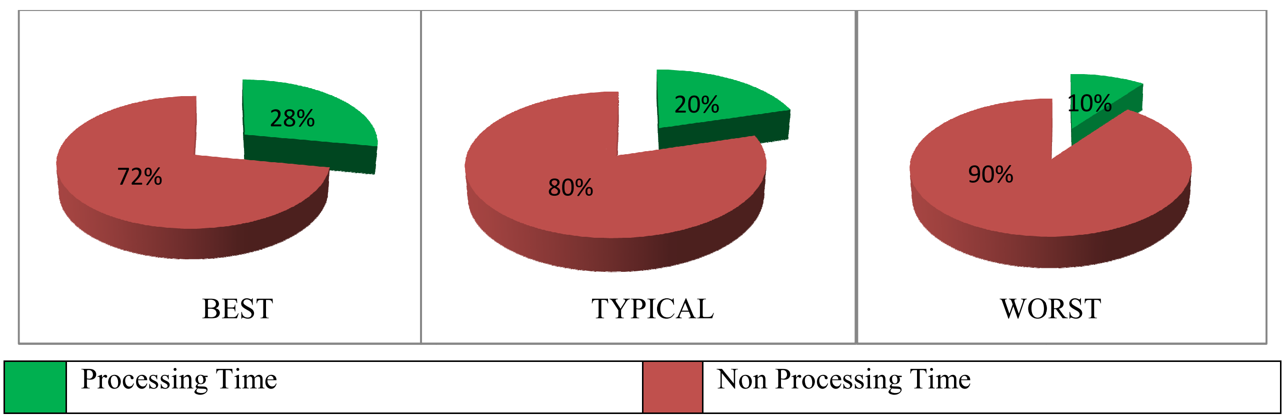

Fig. 6.2: Activity based cycle time distribution – Level 1

Figure 6.2 shows the two components of the overall cycle time with processing time being shown in green and non-processing time shown in red. The initial observation shows that the processing time is only 10 – 28% of the overall cycle time with BEST part having the lowest non-processing time and WORST part being the highest. It is also evident that there are significant improvement opportunities to reduce the overall cycle time by reducing the non-processing times such as movement times, rework times, hold and queue times.

To understand the cycle time in more detail, the non-processing time is further broken down in two more segments: Processing non-value added time (PRT-NVA) and Rework time. Processing non-value added time consists of hold, movement and queue times associated with the actual processing operations of the part. Whereas rework time includes actual rework processing times along with hold, movement and queue times associated with the rework operations. Figure 6.3 shows this further breakdown of the cycle time with processing non-value added time in red and rework time in orange. It can be seen that the rework time can be as low as 0% for the BEST part and can be as high as 61% for the WORST part. In the similar fashion, processing non-value added time accounts for 29% to 72% of the overall cycle time. This shows that the lower housing manufacturing process lacks robustness and has significant variability due to rework, and non – value added times. Rework is one of the major factors in the overall cycle time; however, even this more detailed analysis hides some of the key time consuming factors.

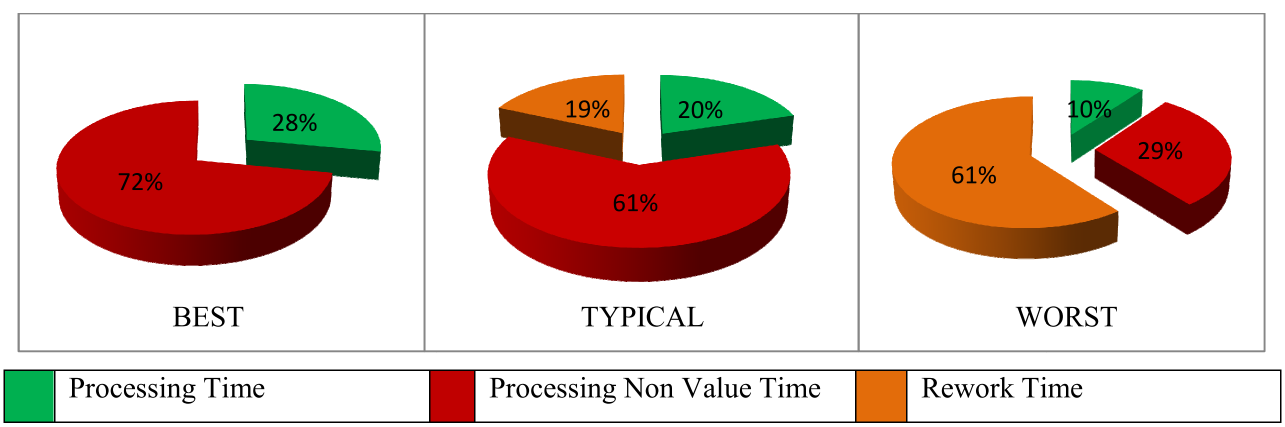

Fig. 6.3: Activity based cycle time distribution – Level 2

The 3rd level of analysis shown in figure 6.4 gives a truer picture of key cycle time issues. The processing queue time varies from 12 – 50% while the processing holding time varies from 15 – 22%. The processing queue time is defined as the total time the part waited in the queue of the machine for the actual operations as defined by the router. The processing hold time is defined as the total time the part waited at the staging area after the actual operations performed on it and the part is ready to be put in the queue for the next operation.

Rework queue time can be as high as 27% of overall cycle time and rework hold time can contribute as much as 17%. The reason that the parts in rework have higher queue and hold time is due to their excessive waiting for machines that are already scheduled to run production parts. Accommodating the rework operations on machines directly affects the overall supply chain of production and thus incurs higher queue and hold times.

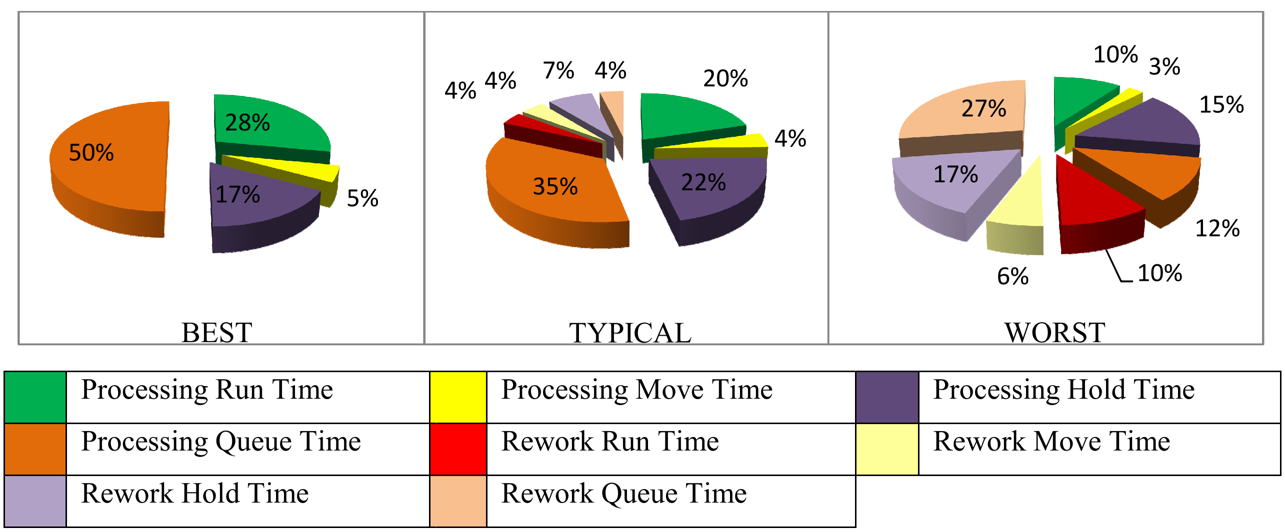

Fig. 6.4: Activity based cycle time distribution – Level 3

6.1.2 Work Center Based Cycle Time Analysis

A work center is defined as the functional step in the manufacturing rather than a physical place where a job is done. The work center based cycle time analysis helps to estimate the total time each part took at each functional steps. The ideal production flow condition is when the part actually touches each functional steps only once during the complete manufacturing (except for QC steps). However, due to severe rework, typically parts come back repeatedly to some of the functional steps resulting in higher cycle times (as well as higher holding and queue time). The various work centers used to produce the lower housings are as follows:

- PULLMAT: The step of pulling the raw materials from the inventory to the staging area in the shop floor.
- BLAST: It defines the functional step where the raw materials are sent for initial shot blasting prior to welding.
- WELD: The step where lower housing components go through a complete weld assembly process. The lower ring, middle ring and upper ring are fit and tacked and then welded together.
- QC2: This step typically includes both NOV and third party inspection prior to certain critical operations. Quality checks evaluate include the right procedures to be followed, materials geometry and positioning, fit up confirmation and dimensional inspection.
- ARC5: At this step, corrosion resistant materials are weld inlaided in the ring groove of lower ring as per the required API weld procedures.
- HTSR: This is a stress relieve heat treatment of the welded parts.

- VTC2500: At this step, the inner diameter and outer diameter of the assembled lower housing are finish machined using turning operations and some face milling and drilling operations on the lower housing flange.
- MILLCNC: In this step the lower housing undergoes finish milling on the side outlet and other final drilling operations.
- DEBUR: This step includes manual deburring to remove burrs formed during machining of lower housing and give the part a clean edge.
- SOV3476 and OSVLK3: These functional steps detail outside vendor operations. Whenever any part is sent outside for processing, it is sent under these functional steps.
- QC1: This step included the inspection of the parts after they arrive from outside vendors.

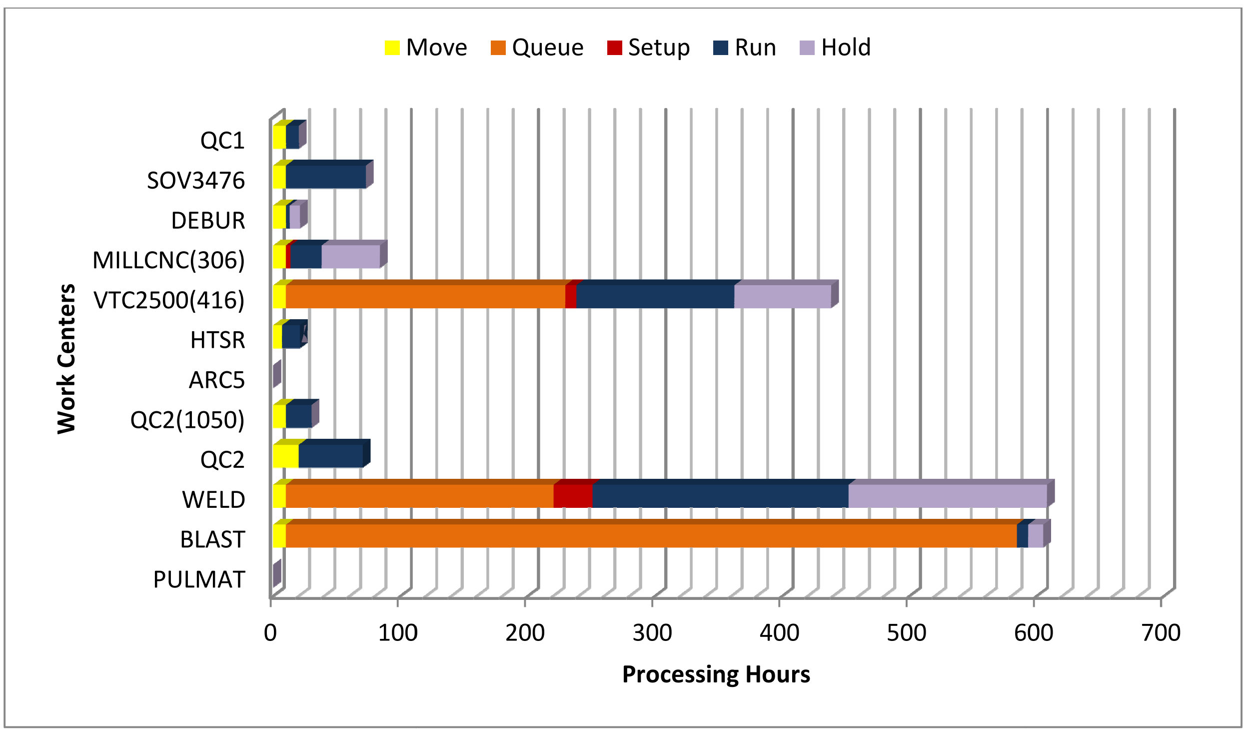

Figure 6.5: Work Center based cycle time analysis for BEST part

Figure 6.5 shows the analysis for the BEST part, which took a total of 96 days to manufacture. The actual processing time including setup and run time was only 28.5% of the total time. It can be noted down that the three work centers BLAST, WELD and VTC2500, account for a total of 84% of the cycle time due to high queue and hold times as well as long processing times. Comparatively all the other work centers contribute either no or very little non value added times (queue and hold times). Even though there is no rework in this BEST production cycle, there is a great room for reducing the non-value added times in order to improve the overall cycle time and productivity.

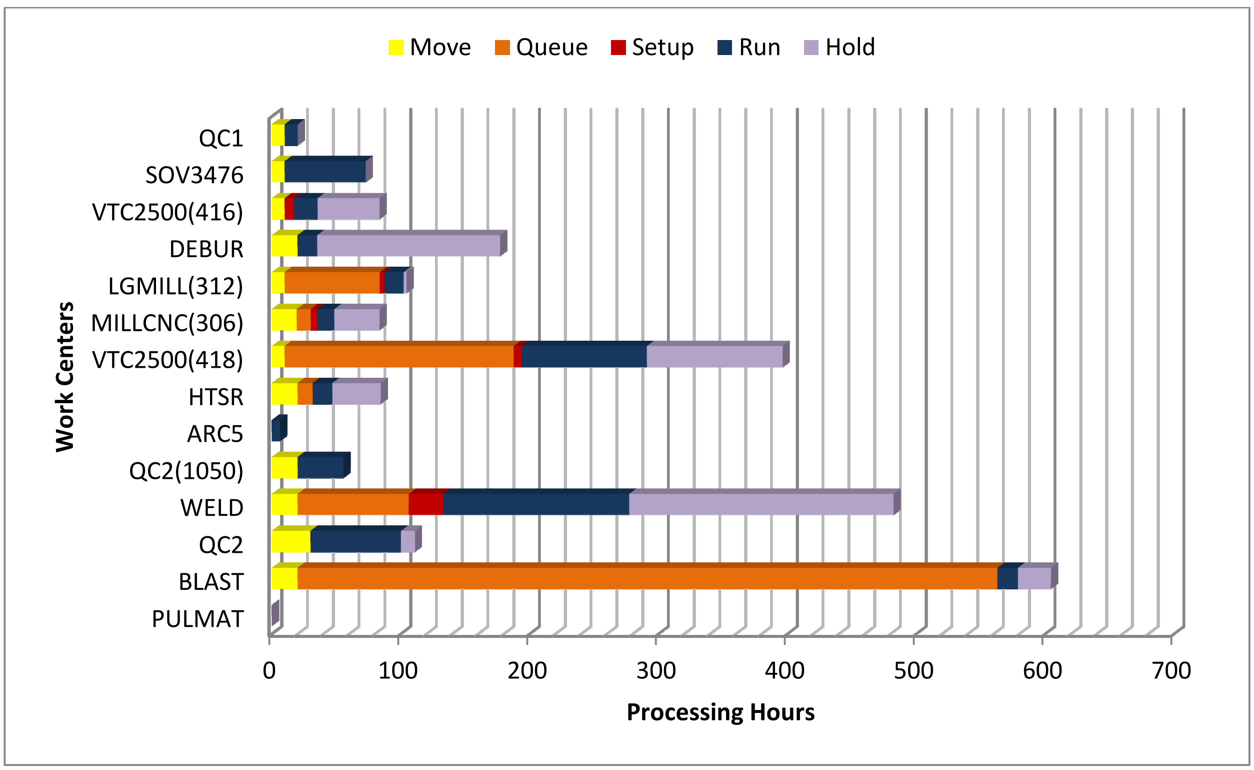

Figure 6.6: Work Center based cycle time analysis for TYPICAL part

Figure 6.6 shows the analysis for the TYPICAL part, which took a total of 110 days to process. The reason for the increase in the cycle time as compared to the BEST part is due to the rework involved. The major portion of the overall cycle time, up to 65%, is still consumed at BLAST, WELD and VTC2500 work centers. However, the analysis also shows that some other work centers now have significant queue and hold times due to rework.

Figure 6.7 shows the analysis for the WORST part, which took a total of 202 days to process. The dramatic increase in the total cycle time is due to the severe rework involved during manufacturing. The WELD work center is the most affected one due to severe rework which alone accounts for 36% of the total cycle time. Also, it is evident that BLAST, WELD and VTC2500 are still the three major work centers which have the most non value added time and are account for 66% of total cycle time.

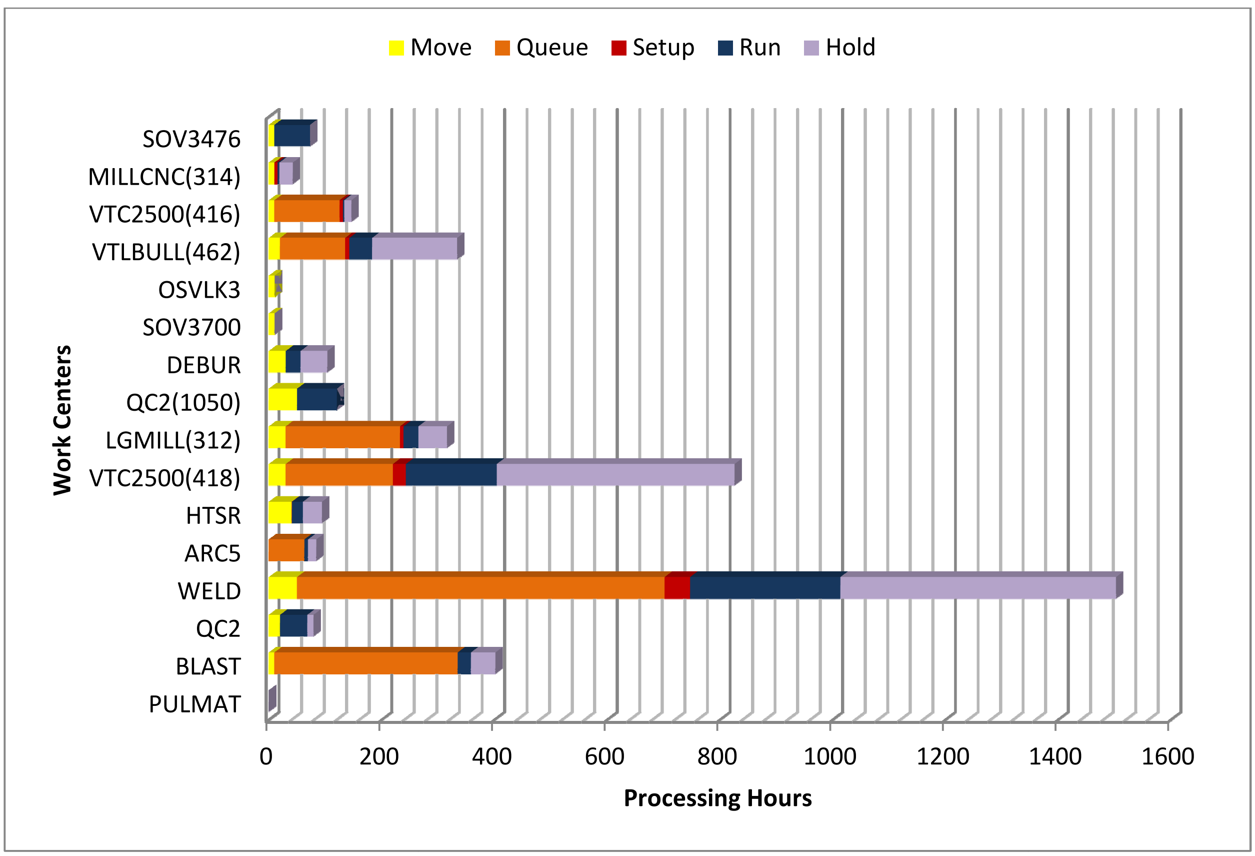

Figure 6.7: Work Center based cycle time analysis for WORST part

Table 6.1: Work Centers with significant Queue and Hold times

	Best	Typical	Worst
# Operations involving Queue	3	6	7
# Operations with significant Queue time	**3**	**4**	**6**
# Operations involving Hold	5	8	11
# Operations with significant Hold time	**2**	**3**	**3**

Table 6.1 shows the total number of work centers with hold and queue time for the BEST, TYPICAL and WORST parts. It also shows the number of work centers with significant hold and queue times. It can be noted that the number of work centers with hold and queue times increases as we move from BEST to WORST due to higher rework associated with the later. As the rework increases, multiple rework operations are being performed on the part at the production work centers. Since, these work centers already has a queue of production parts, the rework parts have to wait longer before they get processed.

The above analysis helps to identify the work centers which should be analyzed in detail to find the root causes for the higher non value added times. However, this analysis doesn't show the various operations that have been performed on a part at a particular work center. Thus the study of operations based cycle time analysis is required in order to estimate the non value added times.

6.1.3 Operations Based Cycle Time Analysis

The operations based analysis is the most detailed analysis. The basis for the analysis is similar to that of the work center based analysis. Non-value added times associated with different operations performed at different work centers are estimated. To discriminate between standard operations and rework operations, company X uses an operation numbering system where each standard operation ends with the digit 0 and each rework operation ends with the digits other than 0.

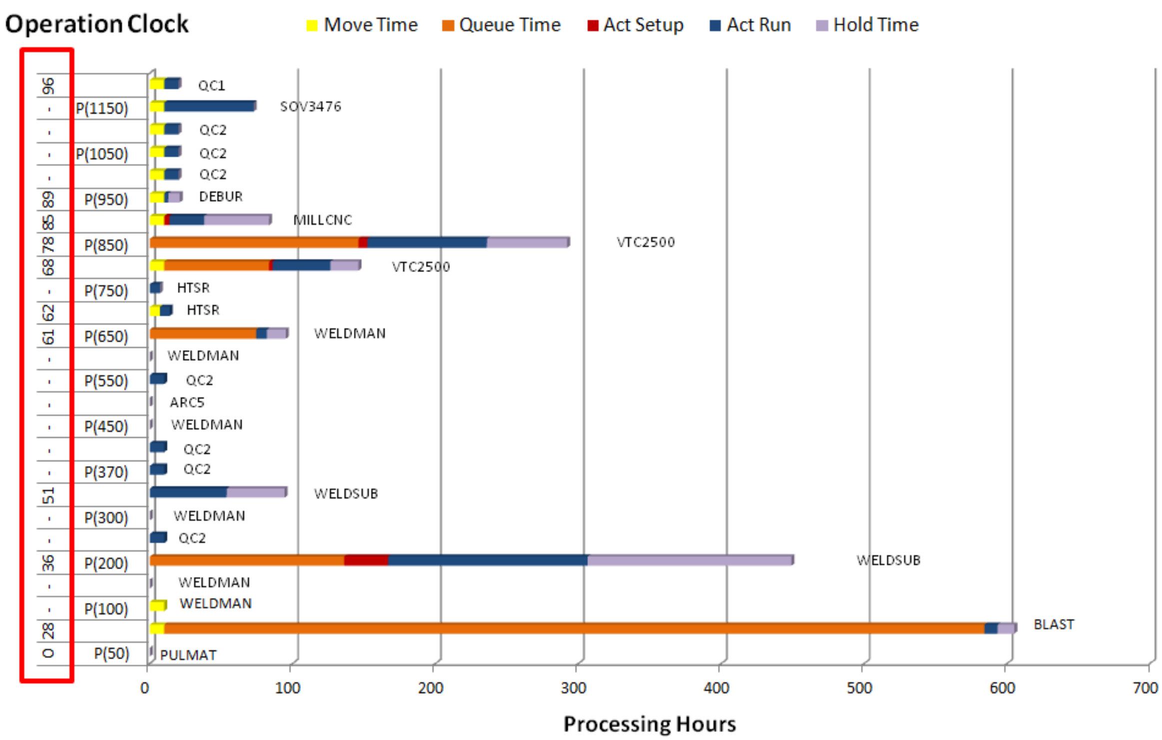

Fig. 6.8: Operations based cycle time analysis for BEST 18/10 lower housing

Figure 6.8 shows the operations based cycle time analysis for the BEST part. The X axis shows the total processing hours for each operation and Y axis shows the different operations at different work centers along with an operation clock (in days). To distinguish between standard operations and rework operations, we have the standard processing operations as 'P' and rework operations as 'R'. It can be noted that the operations WELDSUB and WELDMAN belong to the same work center WELD, even though these are two distinct welding operations. The BEST part underwent 26 operations and took a total of 96 days to process. Five operations namely BLAST (operation number 60), WELDSUB (operation number 200), WELDMAN (operation number 650), and two operations on VTC2500 (operation numbers 800 and 850) have high non value added times and account for the 62% of the overall cycle time. The BLAST operation has the highest queue time of approximately 25 days. The actual processing starts on the 28th day of the total processing days. The reason for this high initial queue time is that the work orders are issued at regular interval of times irrespective of the fact that the shop floor can't accept more parts. Thus, parts are often waiting for long period of time at the staging area.

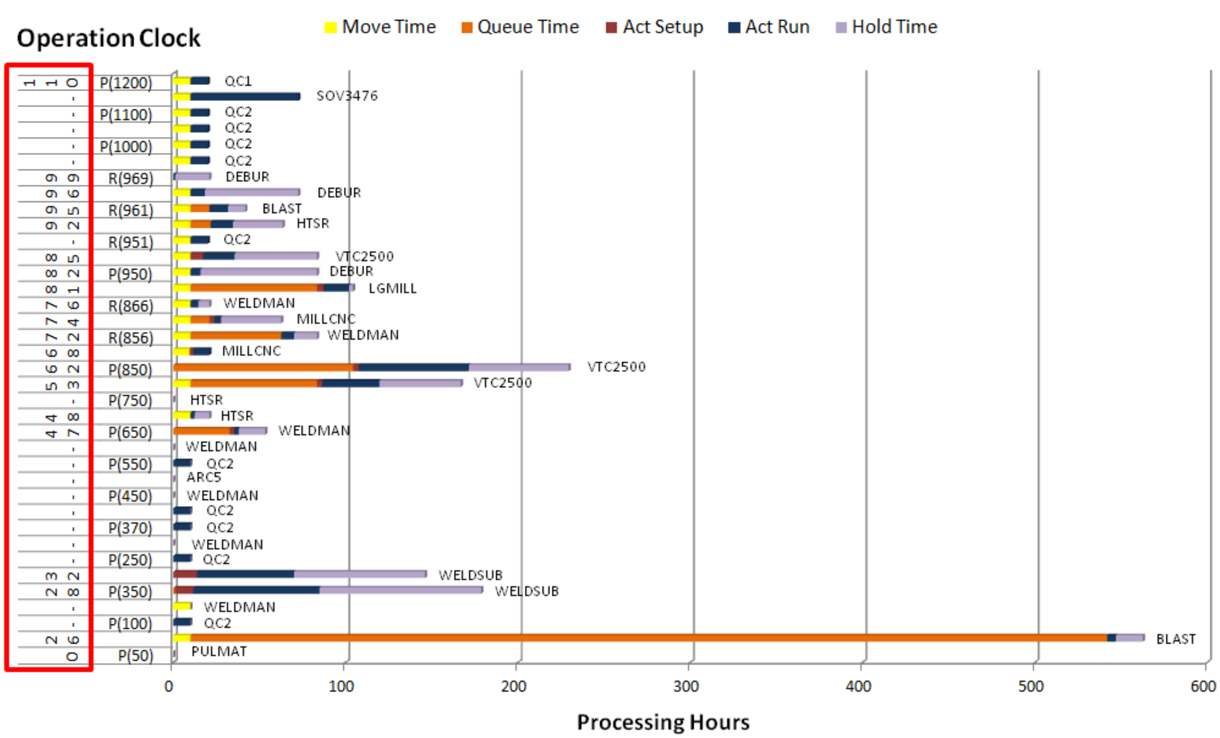

Fig. 6.9: Operations based cycle time analysis for TYPICAL 18/10 lower housing

Figure 6.9 shows the operations based cycle time analysis for the TYPICAL part. The part underwent a total of 37 operations and took a total of 110 days to process. The increase in number of operations (10 additional operations) and the higher number of processing days are due to the rework operations required. The rework operations account for a total of 15% of the overall cycle time. The first rework operation (operation number 851) occurred after the part was halfway through the manufacturing sequence. This resulted in the part to wait longer for the rest of the standard operations as machines were occupied in processing other production parts. Also, the number of QC operations increased as the part had to undergo additional inspections after the rework operations were performed.

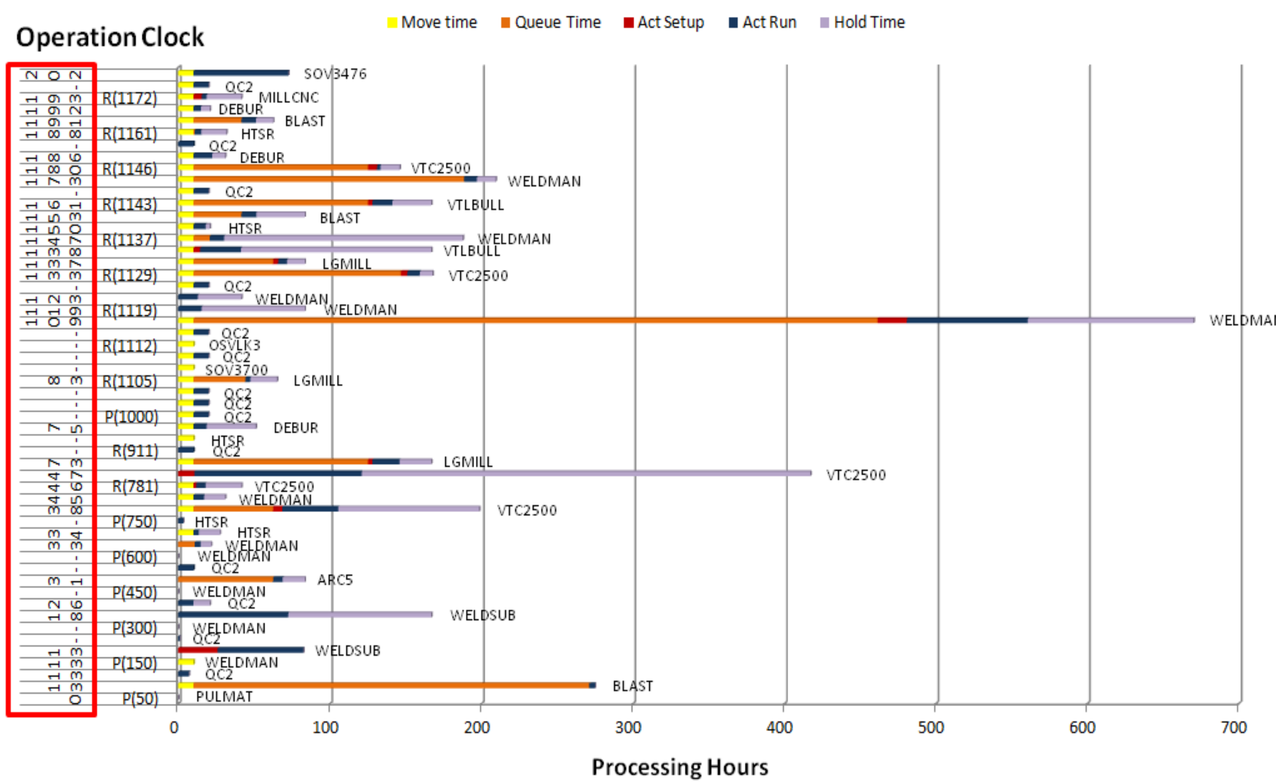

Fig. 6.10: Operations based cycle time analysis for WORST 18/10 lower housing

Figure 6.10 illustrates the operations based cycle time analysis for the WORST part. The part underwent a total of 54 operations and took a total of 202 days to process. The increase in the number of operations (a total of 31 operations) and the additional processing days are due to severe rework involved while manufacturing. The rework resulted in the increase in overall cycletime by 51%. The part underwent 11 rework operations which have more than 100hrs of non value added times associated with them as compared to 3 operations for the BEST part.

Table 6.2: Comparison between BEST, TYPICAL and WORST parts based on rework

Attributes	BEST	TYPICAL	WORST
No. of Operations	26	37	54
Rework Operations	0	10	31
Cycle Time	96 days	110 days	202 days
Non Value Added Times(in %)	67.2%	67.9%	71.1%

Table 6.2 illustrates the effect of rework on the processing of lower housings. It can be concluded that as the rework increases, the number of operations increases with higher non value added times and lower production throughput. In order to achieve the future production demands, the non value added times and rework should be minimized.

6.2 WIP Analysis

Work in process (WIP) or in-process inventory is defined as the average number of units in the system over a time interval. These units are not yet completed but are being fabricated, or are waiting in a queue for further processing or are in buffer storage. Lean concepts consider WIP as waste. Every manufacturer wants to keep WIP to a minimum because:

- WIP includes the cost of committed materials not available for sale
- Cost of storing the WIP

- Long non value added times such as movement times, holding times and queue times increase as WIP increases
- Long lead times and eventually reduced throughput increase with increasing WIP

In order to see the impact of rework on WIP for the BEST, TYPICAL and WORST part, we used the Little's law (Chhajed et. al. 2008) to calculate the WIP for different scenarios.

6.2.1 Little's Law

Little's law relates WIP in a queuing system to the average throughput (TH) and the average time that an item spends in the system (Lead Time, LT). Thus,

$$\text{WIP} = \text{TH} \times \text{LT}$$

This relationship shows that in order to reduce the WIP, we need to reduce the lead time factor by reducing the non value added times. System throughput is driven by the bottleneck machine in the whole manufacturing process. A bottleneck (or constraint) in a supply chain means the resource that requires the longest operation time compared to the other resources of the supply chain. Thus, if the capacity of the bottleneck can be improved then the throughput of the system will increase.

In the present scenario for 18/10 SBOP lower housing manufacture, workstation VTC2500 is bottleneck. The average time it takes to process a part is 137.62 hrs. The utilization of the bottleneck machine also plays a role in determining the expected WIP. As workstation utilization increases (other factors held constant) WIP will also increase. Ideally the utilization for the bottleneck is supposed to be 100%. However, the current utilization of VTC2500 is 49% which is on the lower side. The reason for the lower utilization is due to the higher loading/unloading time of the parts on the machine, the unavailability of the crane for loading and unloading the workstation, machine breakdown, scheduled maintenance of the machine and some QC operations performed on the machine (dimensional checks). Since the parts are very heavy and hard to move, it may be advisable to do some preliminary QC checks on the machine itself. Along with the WIP analyses performed at 49% utilization of bottleneck machine, WIP levels were also estimated at workstation utilizations of 75%.

6.2.2 WIP Analysis for the BEST Part

The overall lead time for the BEST part is 2002 hrs during which it went through different work centers for a total of 26 operations. Figure 6.11 illustrates the flow diagram for the BEST part, processed at different work centers. The solid blue line represents the standard processing operations as defined by the router. Since the part doesn't have any rework operations processing of BEST parts will have less WIP than the processing of TYPICAL or WORST parts.

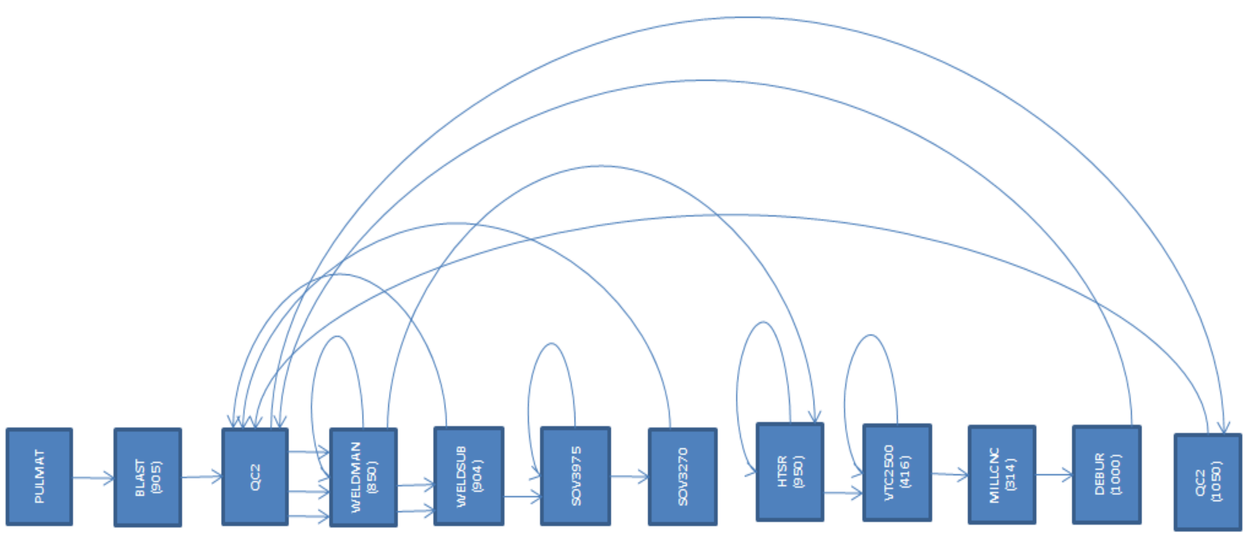

Figure 6.11: Spaghetti flow diagram for the BEST part showing part flow though processing operations

Table 6.3: WIP calculation for the BEST Part

Lead Time (in hrs)	WIP @ 49% utilization	WIP @ 75% utilization
2002	7	11

Table 6.3 illustrates the WIP analysis for the BEST part. It shows that if all the parts are being manufactured as the BEST part with a lead time of 2002 hours and with current bottleneck utilization, then WIP levels of 7 parts will be flowing inside the shop floor at a given time. Also if the utilization of the bottleneck is increased from 49% to 75%, the WIP also increases from 7 to 11, require more staging area to store these parts.

6.2.3 WIP Analysis for the TYPICAL Part

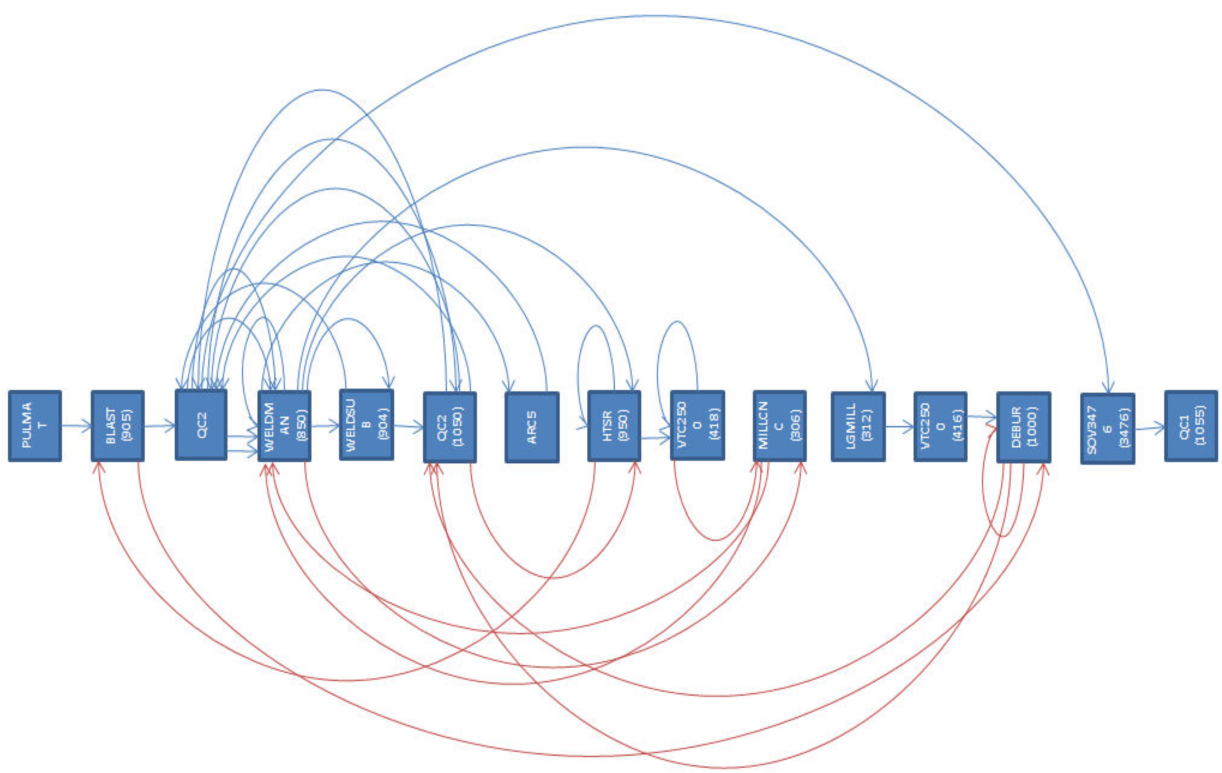

Figure 6.12: Spaghetti diagram for TYPICAL part showing part flow though processing operations

The overall lead time for the TYPICAL part is 2325 hrs during which it goes through different work centers for a total of 37 operations including 10 rework operations. Figure 6.12 illustrates the flow diagram for the TYPICAL part, processed at different work centers. The solid blue line represents the standard processing operations as defined by the router. The solid red line shows the rework operations. Since the TYPICAL part underwent some rework its WIP will also increase since more parts are now waiting at a particular work center at a given time frame.

Table 6.4: WIP calculation for the TYPICAL Part

Lead Time (in hrs)	**WIP @ 49% utilization**	**WIP @ 75% utilization**
2325	8	13

Table 6.4 illustrates the WIP analysis for the TYPICAL part. It shows that if all the parts are being manufactured as the TYPICAL part with the lead time of 2325 hours and with current bottleneck utilization, then we will have 8 WIP units flowing inside the shop floor at a time. Also if the utilization of the bottleneck is increased from 49% to 75%, the WIP also increases from 8 to 13 which will require even more staging area to store these WIP units. The WIP for the TYPICAL part only increases by 14 – 18% as compared to the BEST part as only small rework is involved which results in the increase of overall lead time by only 16%. This situation will drastically change when comparing the results with WORST part WIP analysis.

6.2.4 WIP Analysis for the WORST Part

The overall lead time for the WORST part is 4253 hrs during which it went through different work centers for a total of 54 operations including 31 rework operations. Figure 6.13 illustrates the flow diagram for the WORST part, processed at different work centers. Since the part required excessive rework hours and operations, there will be dramatic increase in WIP as workstation utilization increases.

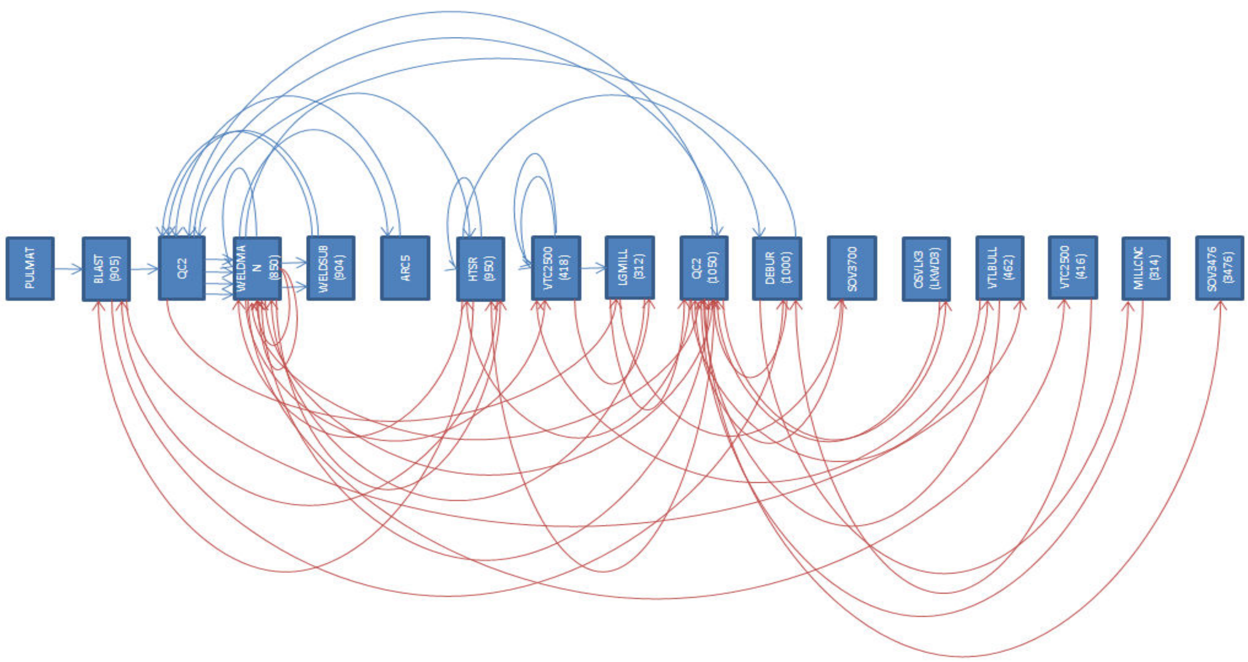

Figure 6.13: Spaghetti diagram for the WORST part showing part flow though processing operations

Table 6.5: WIP calculation for the WORST Part

Lead Time (in hrs)	WIP @ 49% utilization	WIP @ 75% utilization
4253	15	23

Table 6.5 illustrates the WIP analysis for the WORST part. It shows that if all the parts are being manufactured as the WORST part, with the lead time of 4253 hours and with current bottleneck utilization, then we will have 15 WIP units flowing inside the shop floor at any given time. Also if the utilization of the bottleneck is increased from 49% to 75%, the WIP also increases from 15 to 23 which will require even more staging area to store these WIP units as compared to the BEST and TYPICAL parts. The WIP for the WORST part increases by 109 - 114% as compared to the BEST part as it got affected by huge rework. The lead time also increased by 112% as compared to the BEST part.

6.3 Throughput Analysis

Key performance indices (KPIs) are assorted variables that organizations use to assess, analyze and track manufacturing processes. These performance measurements are commonly used to evaluate success in relation to goals and objectives. One of the goals of this study is to measure the yearly production capability or capacity for lower housing manufacturing. Since every year the demand is increasing, thus we must know whether company X has the capacity to fulfill the demand for lower housing or it needs to outsource some of production to an outside vendor. The throughput of a manufacturing system is defined as the rate of production of the system over a specific amount of time. It is a KPI of a production system.

The lower housing manufacturing involves several machines (work centers) to perform different operations at different stages. The top two work centers having long lead times are VTC2500 and WELD. The rest of the work centers have smaller lead times for manufacturing. Since the throughput is defined by the bottleneck machine, and VTC2500 is the bottleneck in lower housing manufacturing, the production throughput will be driven by bottleneck lead time. However, analysis will show that the bottleneck can shift to WELD operations if a different strategy for production is utilized. The various strategies to analyze the throughput will be discussed later on in this chapter in detail. There are two machines (machine no. 416 & 418) that can perform operation VTC2500, but only 416 is fully dedicated to lower housing manufacturing. Machine 418 is a shared resource that can be used depending on its availability.

6.3.1 Throughput Analysis for VTC2500

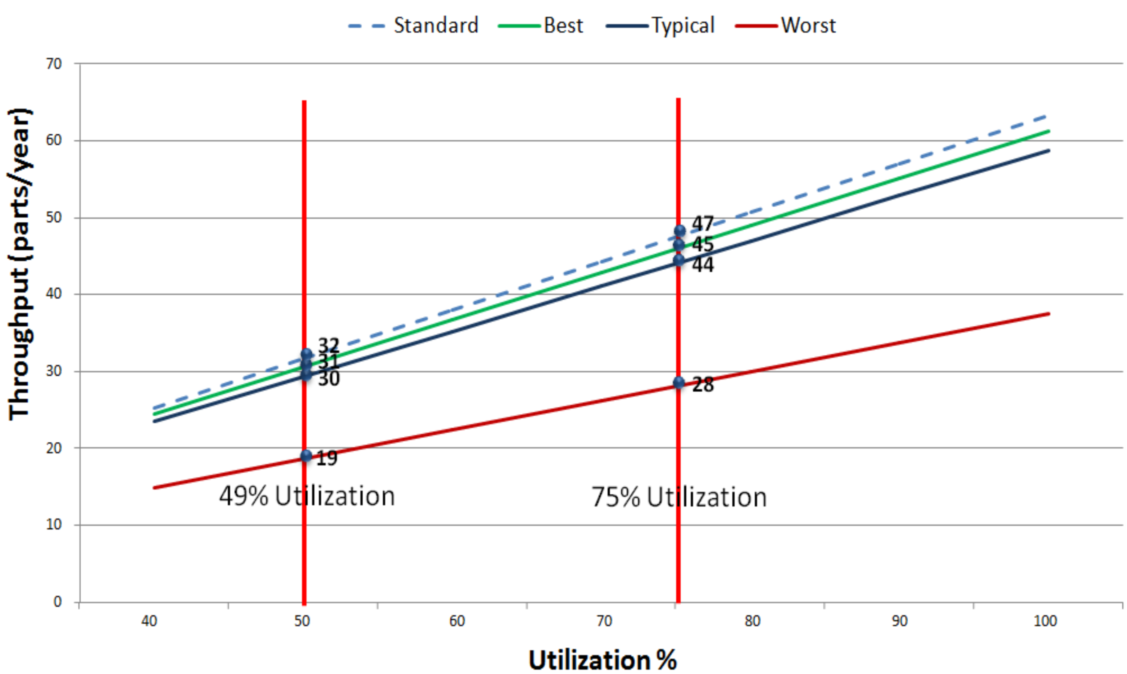

Figure 6.14: Throughput analysis for VTC2500 – 416 at current workstation utilization (49%) and at 75% workstation utilization

Figure 6.14 illustrates the throughput analysis for VTC2500 – 416 based on the lead times for STANDARD (the dotted blue line), BEST (the green line), TYPICAL (the solid dark blue line) and WORST (the red line) parts. The standard lead time is defined by the set routing hours for the machining of the lower housing from the standard router. However, in reality the lead time varies which is evident by the lead times of BEST, TYPICAL and WORST parts. In this analysis, it has been assumed that all parts are produced per year with the lead times of STANDARD, BEST, TYPICAL and WORST part lead times respectively, then we will achieve throughput shown by the dotted blue line, the green line, the solid dark blue line and the red line.

The current utilization for VTC2500 is 49% and if throughput is estimated with 49% utilization of the machine throughout the year then it can lead us to produce 19 parts/year, 30 parts/year, 31 parts/year and 32 parts/year for parts with processing the characteristics of WORST, TYPICAL, BEST and Standard parts. In the present analysis it has also been showed that if we can increase the utilization of 416 from 49% to 75% then we can increase the production throughput by 46.5% on average.

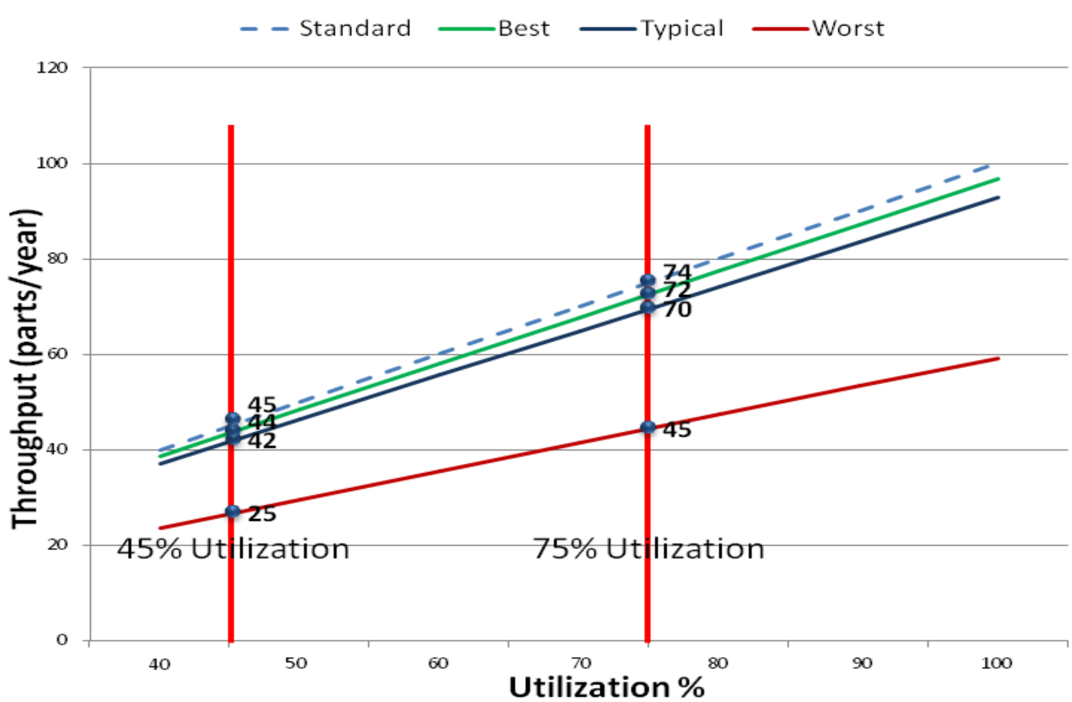

Figure 6.15: Throughput analysis including hidden capacity of machine 418 at utilization of 45% and at utilization of 75%

Figure 6.15 illustrates the throughput analysis for the combined use of two VTC2500 machines. The calculation is based on the total available capacity of machine 416 and the hidden capacity of machine 418 that can be shared to increase the production of lower housing. The current utilization of machine 418 is 42% and thus the hidden capacity or extra capacity available is 58% of the total available hours. The present analysis shows that if machine 416 is only utilized for 45% and the hidden capacity for machine 418 is also utilized for 45% then productivity can be increased by 38.5% on average compared to the throughput of machine 416 utilized at 49%. Similarly if the utilization for machine 416 is increased to 75% along with the use of 75% of the hidden capacity for machine 418 then productivity can be increased by 133% on an average compared to the throughput by machine 416 with 49% utilization.

6.3.2 Throughput Analysis for WELD Operations

The WELD consists of WELDMAN and WELDSUB operations. In the WELDMAN operation, the parts are prepared for the welding operation including face and edge, joint preparation. The WELDSUB operation is the actual welding operation to join the major components together.

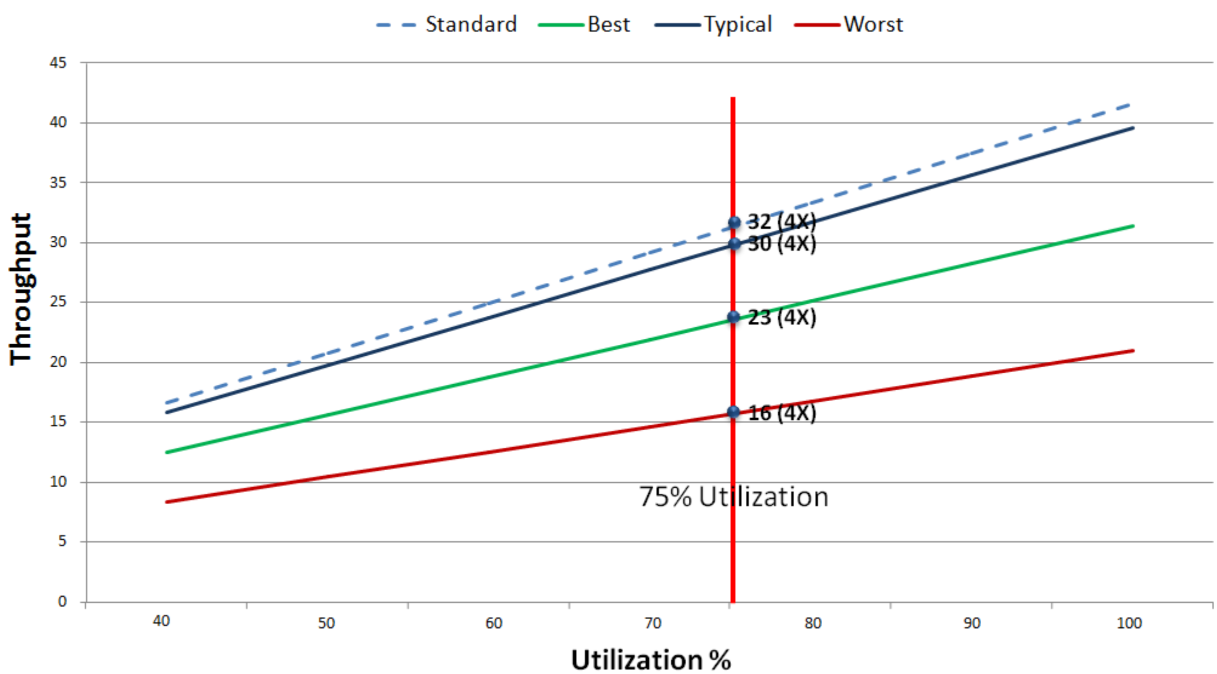

Figure 6.16: Throughput analysis for combined WELD operations at different workstation utilizations

Figure 6.16 illustrates the throughput analysis for WELD operations for STANDARD, BEST, TYPICAL and WORST parts. The analysis is based on the total available hours of 7592 hrs/yr for welding and 75% utilization. It is interesting to note that the TYPICAL part performed well compared to the BEST part. Also, since there are four weld positioners available to do process the parts, a multiplying factor of 4 has been used to estimate overall throughput. Based on the lead time for the WORST part and assuming all parts are produced at this lead time, a throughput of 16 parts/yr per positioner or 64 parts/yr can be achieved using all four fixtures at 75% utilization. Similarly, overall throughput of 92, 120 and 128 parts/yr can be achieved if the parts are being produced at the lead times of BEST, TYPICAL and STANDARD parts respectively. If we compare these estimated throughputs to the machining analyses from 6.3.1 and 6.3.2, it can be noted that the VTC2500 machining operation is the bottleneck operation. However, in the next section we will discuss different scenarios for throughput analysis that indicate that the bottleneck shifts from VTC2500 to WELD depending on production assumptions.

6.3.3 Throughput Scenarios

Table 6.6 illustrates the various scenarios for analyzing the throughput for lower housing production. The basis for the calculations for these scenarios is bit different than the previous throughput calculations. It has been assumed that all the machines are available to run for 24hrs a day and 365 days a year i.e. 8640hrs/year. Also, the utilization for the bottleneck machine was assumed to be 100% to calculate the maximum throughput the system can achieve. However another set of more realistic throughput calculations have been done at 80% utilization of the bottleneck machine (shown inside the brackets).

Table 6.6: Different throughput scenarios

Scenarios	Production Capacity (units/month)						Throughput (units/yr)
	WELDSUB	ARC5	HTSR	VTC2500	MILLCNC	DEBUR	
1. One WELD Positioner	**5 (4)**	23	17	6 (5)	28	180	**60 (48)**
2. One extra WELD Positioner	10 (8)	23	17	**6 (5)**	28	180	**72 (60)**
3. Advanced Jigs & Fixtures + Scenario 2	**10 (8)**	23	17	12 (10)	28	180	**120 (96)**
4. One WELD Positioner + Advanced Jigs & Fixtures + Outsourcing for WELD	**10 (8)**	23	17	12 (10)	28	180	**120 (96)**
5. Scenario 2+ Outsourcing for VTC2500	**10 (8)**	23	17	12 (10)	28	180	**120 (96)**

Scenario 1 assumes that if we have only one dedicated WELD positioner to carry out the welding operation then the bottleneck shifts to WELD which can only produce a total of 5 units/month at 100% utilization or 4 units/month at 80% utilization. The rest of the machines except VTC2500 are well above these throughput thresholds. The yearly production achieved by this scenario is 60 units at 100% utilization or 48 units at 80% utilization for the bottleneck machine.

Scenario 2 assumes that another dedicated WELD positioned is added. Then the production for WELD is doubled and the bottleneck shifts to VTC2500 which can produce 6 units/month at 100% utilization or 5 units/month at 80% utilization. The maximum annual production achieved by this scenario is 72 units.

Scenario 3 assumes that there are two dedicated WELD positioners and that advanced jigs and fixtures are used for VTC2500 which can reduce the run time for VTC2500 by 50%. In this scenario the bottleneck shifts back to WELD. The production for the bottleneck is 10 units/month at 100% utilization and 8 units/month at 80% utilization. The maximum annual throughput achieved by this scenario is therefore 120 units.

Scenario 4 and scenario 5 involves outsourcing option for the bottleneck operation which is another way to increase the production. Scenario 4 assumes that there is only one dedicated WELD positioner, advanced jigs and fixtures are used for VTC2500 and the production equivalent to one dedicated WELD positioned is outsourced. With this option an annual maximum production of 120 units is possible. Scenario 5 assumes that we have two dedicated WELD positioners and that the outsourced production is equivalent to one VTC2500 machine, but no use of advanced jigs and fixtures. With this option an annual production of 120 units is possible.

6.4 Root Cause Analysis

Root Cause Analysis is a method that is used to address a problem or non-conformance in order to get to the “root cause” of the problem. There are different tools that can be used to perform a root cause analysis, including -using a Fishbone representation for this purpose as done in this analysis. Company X employees who are part of lower housing manufacture were interviewed, to find out the reasons or the root causes for production delays and the top four NCRs - Weld Fabrication, Weld Inlay, Weld Non-Inlay and Operator Error. The survey was categorized into 5 different categories namely people, assembly/machine, methods/process, materials, and environment. Everyone who took the survey identified the problem root cause from different root cause categories. Fishbone diagrams were constructed based on the responses.

6.4.1 Delay in the Process Root Cause Analysis

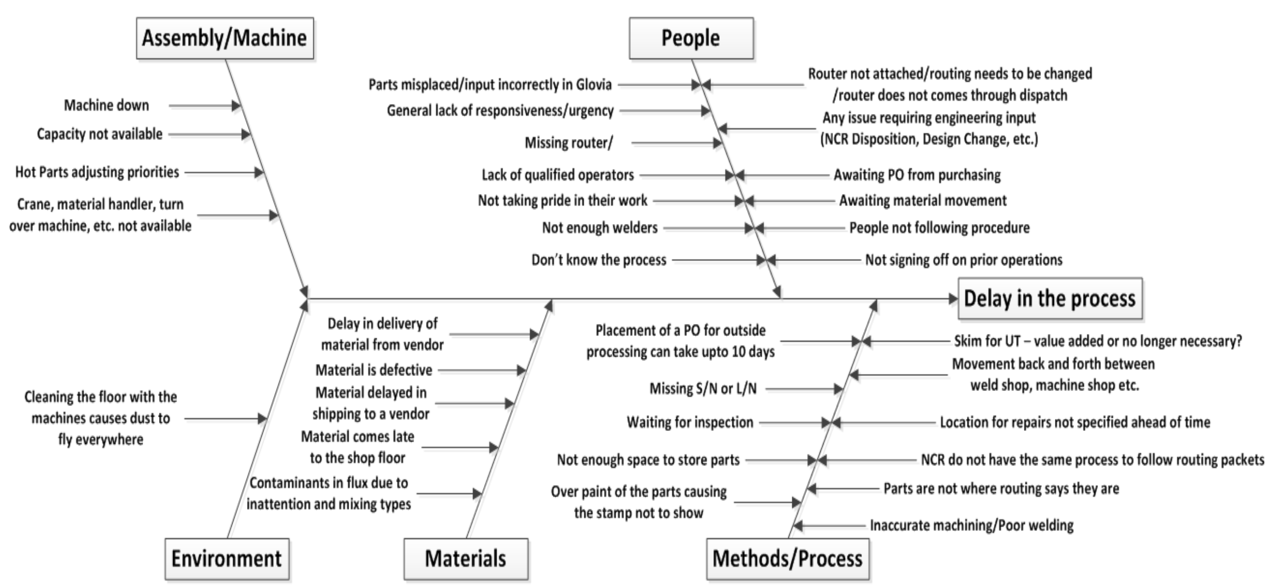

Figure 6.17: Fishbone diagram for production delay root causes based on employee surveys

A total of 34 reasons for delays were recorded. Thirteen were related to the people category, 11 related to methods/process, 5 related to materials, 4 related to assembly/machine and 1 related to the environment. Figure 6.17 illustrates the fishbone diagram for the root causes for delay in the process. Out of these reasons the top 8 reasons mentioned by almost everyone were - inaccurate machining/poor welding, issues requiring engineering input, delays associated with awaiting material movement, machine downtime, hot parts causing adjusted priorities, delays in the delivery of the materials from vendor, not enough space to store parts, and waiting for inspection.

6.4.2 WELD Fabrication NCRs Root Cause Analysis

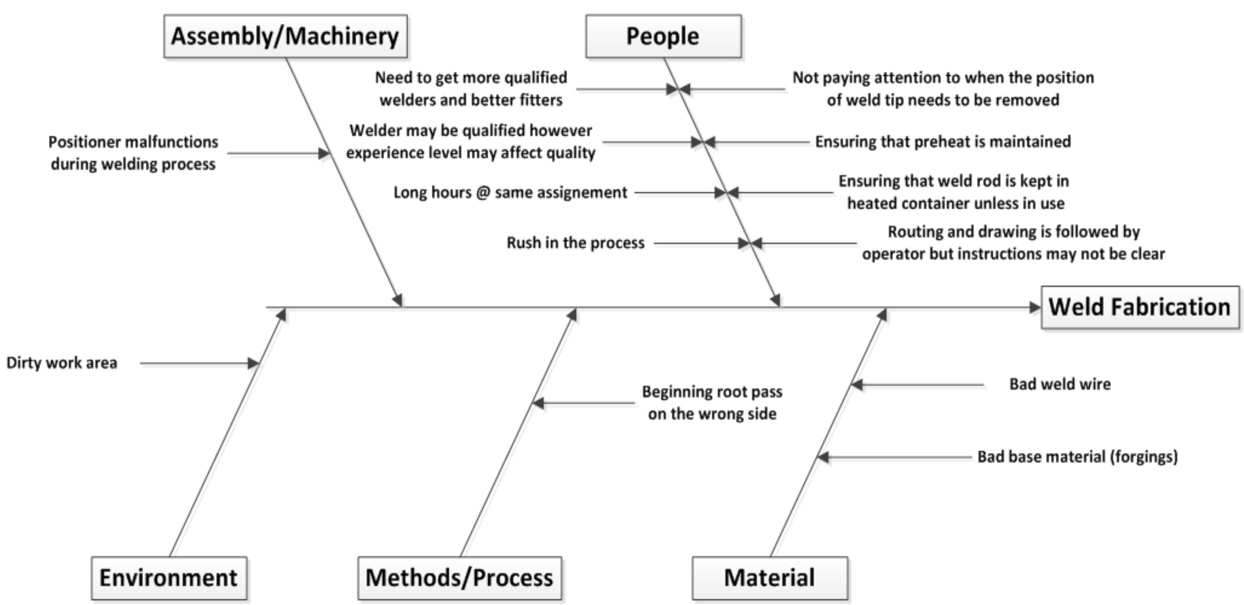

Figure 6.18: Fishbone diagram for the WELD Fabrication NCRs root causes based on employee surveys

A total of 13 reasons were received belonging to the root cause for WELD Fabrication NCRs with 8 related to the people category, 1 related to methods/process, 2 related to materials, 1 related to assembly/machine and 1 related to environment. Figure 6.18 illustrates the fishbone diagram for the root causes for WELD fabrication NCRs. Out of these reasons the top 3 reasons mentioned by almost everyone were - ensuring that weld preheat is maintained, the need for more qualified welders, and bad weld wire.

6.4.3 WELD Inlay NCRs Root Cause Analysis

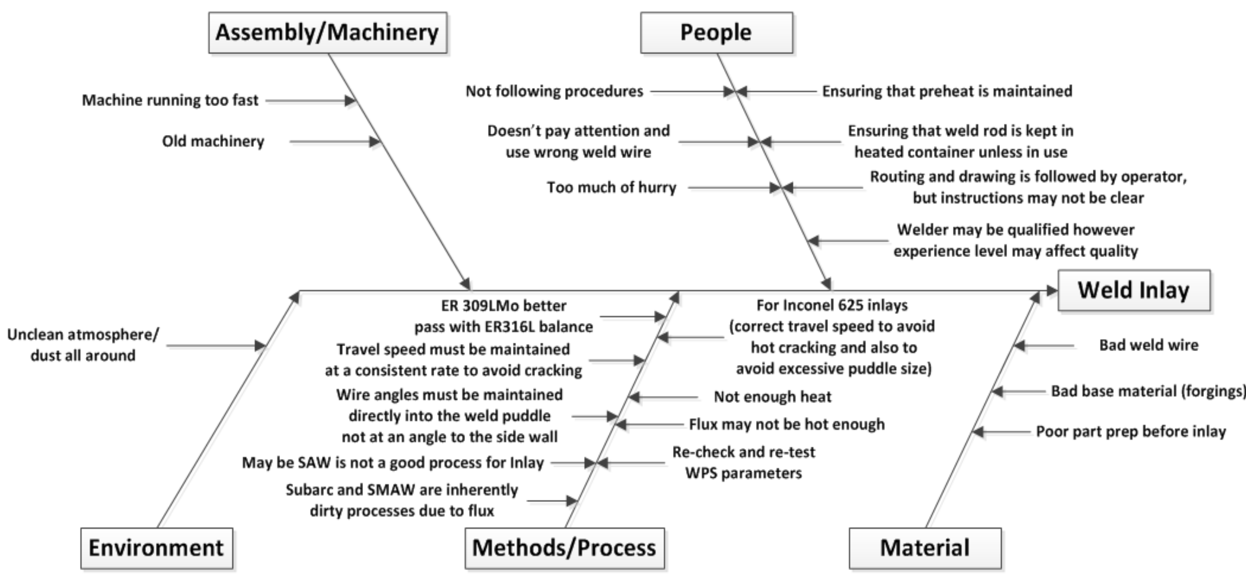

Figure 6.19: Fishbone diagram for the WELD Inlay NCRs root causes based on employee surveys

A total of 22 reasons for WELD Inlay NCRs were identified with 7 related to people category, 9 related to methods/process, 3 related to materials, 2 related to assembly/machine and 1 related to environment. Figure 6.19 illustrates the fishbone diagram for the root causes for WELD Inlay

NCRs. Out of these reasons the top 5 reasons mentioned by almost everyone were - not following weld procedures, poor part preparation before inlay, not enough pre-heat, bad welding wire, and the need for more qualified welders.

6.4.4: WELD Non-Inlay Root Cause Analysis

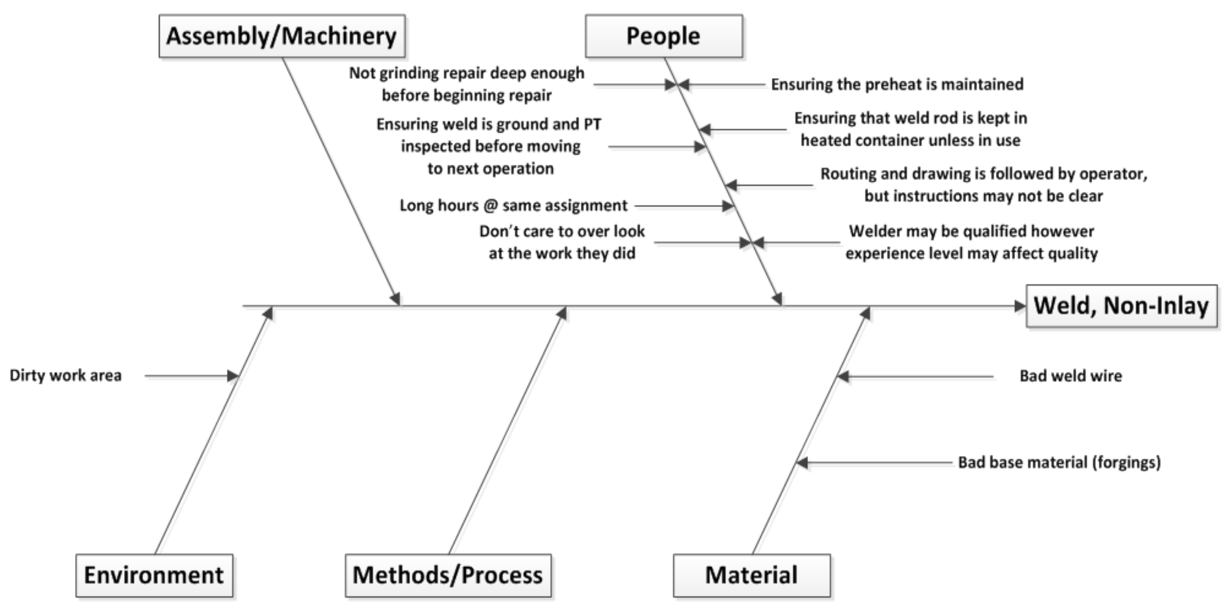

Figure 6.20: Fishbone diagram for the WELD Non-Inlay NCRs root causes based on employee surveys

A total of 11 reasons were identified for WELD Non-Inlay NCRs with 8 related to people, 2 related to materials, and 1 related to environment. Figure 6.20 illustrates the fishbone diagram for the root causes for WELD Non-Inlay NCRs. Out of these reasons, the top 3 reasons mentioned by almost everyone were - not enough pre-heat, bad welding wire, and the need for more qualified welders".

6.4.5: Operator Error NCRs Root Cause Analysis

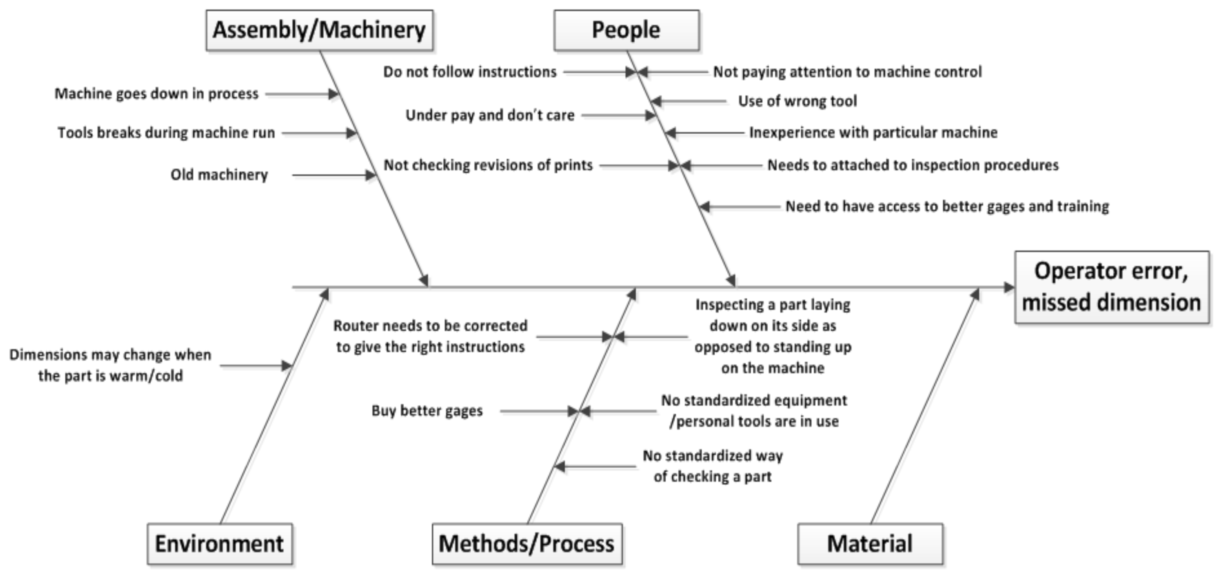

Figure 6.21: Fishbone diagram for the Operator Error NCRs root causes based on employee surveys

A total of 17 reasons were received for Operator Error NCRs with 8 in the people category, 5 for methods/process, 3 for assembly/machinery and 1 for the environment. Figure 6.20 illustrates the fishbone diagram for the root causes for Operator Error NCRs. Out of these reasons, the top 4 reasons mentioned by almost everyone were – a need for access to better gages and training, instructions not being followed, tool breakage during machining run, and the use of wrong tools.

6.5 Rework Cost Analysis

Rework is defined as the unnecessary effort of redoing a process or activity that was incorrectly implemented the first time. The rework cost is the actual direct cost that is spent on correcting defective work. Generally, in the production system of company X, the rework cost gets overlooked and is not identified as a separate operating cost, but is a part of job order closure variance (JOCV). JOCV is defined as the difference between the standard cost of the job to the actual cost of manufacturing of that particular job. The higher the rework, the higher is the JOCV.

One of the goals for this study is to quantify the effect of the rework on the lower housing manufacturing cost. The analysis was done on the BEST, TYPICAL and WORST parts. The BEST had no rework and the WORST had the most rework. However the analysis is purely based on the rework direct labor cost analysis since corresponding data on materials consumed during rework, total time taken in doing QC for rework, and any other indirect labor that was involved in processing rework is not measured. To carry out this analysis, a direct labor rate of $300/hr is assumed. With this assumption the standard direct cost of manufacturing an 18/10 lower housing is $350,000.

6.5.1 Rework Direct Labor Cost Analysis

Table 6.7 illustrates the rework direct labor cost analysis for BEST, TYPICAL and WORST parts. The WORST having the highest rework, took an additional 10% of overall cycle time for rework operations. The added labor cost due to rework to the standard cost was $129,600 which was 37% of the total cost of manufacturing for the lower housing. This additional cost is only for direct labor and doesn't include any material cost or indirect labor cost, which would increase the cost of rework even further. Similarly, the TYPICAL part accrued a total of $25,200 for direct labor rework cost which is 7.2% of the total cost of manufacturing for an 18/10 lower housing.

The BEST part doesn't have any cast variance due to rework because it doesn't have any rework involved.

Table 6.7: Rework direct labor cost analysis

Part Description	Rework Time (in hrs) In % of overall cycle time	Rework Direct Labor Cost	% of lower housing standard cost
WORST	10%	$129,600	37%
TYPICAL	4%	$25,200	7.2%
BEST	0	0	0

6.5.2: Analysis for Direct Labor Cost for Major NCR's

Figure 4.3 from chapter 4 highlighted the top four NCRs related to Weld Inlay, Weld Fabrication, Weld Non-Inlay and Operators Error, which accounted for 60% of the total NCRs during lower housing manufacture. This analysis quantifies the direct labor cost associated with these major NCR reasons to identify their impact on the total cost variance.

Table 6.8 illustrates that NCRs related to Weld Fabrication contributed the most (53.7%) to the total rework direct labor cost for the WORST part. The rest of the NCR reasons contributed 15.6% to the cost variance. It should be noted that all these NCR reasons don't sum up to 100% for the total rework labor cost since some of the rework data was not categorized and therefore couldn't be quantified. Similarly for TYPICAL part, the Operator Error NCR reason contributed the most (74.4%) to the total rework direct labor cost.

Table 6.8: Analysis for direct labor cost for major NCRs

Type of NCR	Rework Processing Hrs (Setup + Run)			% of Total Rework Direct Labor Cost		
	WORST	**TYPICAL**	**BEST**	**WORST**	**TYPICAL**	**BEST**
Weld, Inlay	15	0	0	3.5%	0	0
Weld, Fabrication	232	0	0	53.7%	0	0
Weld Non-Inlay	43.5	0	0	10.1%	0	0
Operators Error	8.7	62.5	0	2%	74.4%	0

6.6 Discussion

The focus of this study was to conduct the first detailed analysis of 18/10 lower housing cycle time in order to identify and quantify non value added times during manufacturing. The results from the cycle time analysis also pointed towards poor performing bottleneck work centers which have a direct impact on production throughput.

Once the cycle time analysis was established, the effort shifted towards a WIP analysis. The output from the cycle time analysis became the vital input for WIP calculations. The WIP analysis gave valuable information about the average number of units flowing through the shop floor during a given time frame. This WIP analysis was useful in deciding the number of staging locations to be placed inside the shop floor to handle the WIP and in scheduling the manufacturing of the 18/10 lower housings in more efficient ways. The WIP increased dramatically from the BEST part to WORST part production scenarios (more than 100%) due to the involvement of rework and non value added time increases.

A comprehensive production analysis begins with an assessment of production capacity or throughput identification of the bottleneck operation that drives the throughput of the system. This throughput analysis was based on three important parameters - the total available production hours for the bottleneck machine, its utilization, and its lead time to process a single unit. Also, various different scenarios were evaluated during the analysis to see the maximum throughput possible with different production assumptions. It was also interesting to see the shift in the bottleneck from one machine to another for the various production assumptions.

Another goal for the study was to find the root causes for the delay in the process and for the major NCR reason codes. The major NCR category is defined by the number of occurrences during manufacturing in a financial year. In the present study, the top 4 NCR reason codes accounted for more than 60% of the total NCRs for the year. Production employee survey results were used to identify root causes which were later on mapped to the results found out during the analysis. Table 6.9 shows some of the root causes mapped to the results from the production analysis.

Table 6.9: Mapping of root causes to production analysis results

Root Cause	Analysis Result
Awaiting material movement	Higher movement times
Machine down	Higher queue times, lower utilization of machine
Qualified welders and bad weld wire	Higher rework
Tool breaks during machining	Lower utilization for bottleneck machine
Unloading of parts from machine	Lower utilization for bottleneck machine

Company X always currently reports only the overall JOCV for each job done. The JOCV can be very low or very high depending on the rework or extra hours put in the job. However, these JOCV impacts were never quantified by the NCR code causing the variance and by how much. In this analysis, only direct labor costs for sources of variance caused by these NCR codes have been quantified, but there is no system in place to track the materials used during rework. A better estimation of raw material consumption and indirect labor costs during rework should be done in future to give a better rework cost assessment for each NCR reason code.

Chapter 7

Conclusions

7.1 Conclusions and Future Work

A first detailed data driven analysis has been developed to study the complex nature of large bore 18/10 SBOP lower housing manufacture in terms of cycle time, throughput and rework. These analysis techniques can be applied to other large, custom engineered, long lead time products whose production costs and lead times are driven by similar factors.

For the present analysis, production data for 29 parts; all of them with different cycle times and different level of reworks were studied. However, because of the sheer volume of production information that needed to be analyzed a thorough analysis of three representative parts based on the number of operations and amount of rework (identified as BEST, TYPICAL and WORST) were comprehensively evaluated. The WORST part demonstrated the highest non value added times in terms of holding and queue times and lowest throughput. It has also the highest estimated WIP levels. Though rework had the main impact on the cycle time and throughput, the low machine utilization and the unavailability of cranes to handle the parts also contributed greatly to production inefficiency. The BEST part on the other hand had the minimum cycle time, lowest WIP and the highest throughput. However, non value added times for the BEST part still had a significant impact on throughput. The JOCV certainly increased due to the increase in rework for TYPICAL and WORST parts which ultimately reduce profit margins significantly. The analysis has also shown useful findings in terms of root causes for the delays, major NCRs and staging area requirements. However, further study of additional production parts is needed to insure that the results described here can be generalized for all production parts.

Additional study should evaluate additional production scenarios for increasing throughput, scheduling analyses for bottleneck machines and cranes, NCR elimination, and detailed time study and evaluation of indirect cost associated with production inefficiencies. Following specific recommendations for more detailed study have been identified:

1. **Detailed VTC2500 study:**

   A comprehensive scheduling study for VTC2500 is needed to understand the reasons for its low utilization. Theoretically, the bottleneck should have the utilization close to 100%, however VTC2500 currently has only 49% utilization. Careful study of scheduling for part arrival at VTC2500, part loading/unloading, processing time reduction, job holding jigs and fixtures and staging areas near VTC2500 to prevent workstation blocking and starving should be carried out.

2. **Crane scheduling study:**

   At present only one crane serves the whole 18/10 lower housing production area and causing it to be used at each and every machine for parts loading/unloading. Because parts are heavy, take time to move from one location to other, and only one part can be handled one time, it is likely that the delays in loading and unloading machines are a significant part of low machine utilization. Thus a detailed scheduling study for crane is required to see how it is being used and how crane priorities are being set if two parts are waiting to be loaded at the same time.

3. **Weld Inlay materials analysis:**

   We have seen that one of the top NCR is due to defects during weld inlay. Thus a detailed metallurgical study is required to evaluate inlay materials and processing operations to identify weld quality deficiencies and identify improvements in inlay materials and processes to reduce inlay NCRs.

4. **Gage R & R study:**

   A dimensional measurement system Gage R & R study is needed to determine if dimensional inspection systems (tools, procedures and operators) are adequate. This will be the first step in the process needed to identify sources of dimensional non-conformance and to take preventive action to assure dimensional conformance and to minimize inspection costs.

5. **One piece forging analysis:**

   The cutting edge technology for the development of a lower housing one piece forging is in process to replace the three piece forging which eventually get welded together to form the current lower housing body. The additional cost of complex one piece forging procurement must be justified based on reductions in total welding and welding rework cost. Reduction in welding NCRs and welding rework costs will significantly lower the overall costs associated with three piece forging production compared to the cost of procured one piece forgings.

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Appendix A: Production Data Set

A.1 Production Data Set for BEST Part with Transaction Dates

Work Center	Machine	Operations	Total Time (in Hrs)			First Trx	Last Trx	Issue Date	Manu. Close
			Act Run	Act Setup	Move Time				
PULMAT	PULMTL	P(50)	0	0				1/6/11	
MOVE					10				
BLAST	905	P(60)	9.22	0		2/3/11	2/3/11		
MOVE					10				
WELDMAN	850	P(100)	0	0					
WELDMAN	850	P(150)	0	0					
WELDSUB	904	P(200)	139.73	30.60		2/11/11	2/25/11		
QC2		P(250)	10	0					
WELDMAN	850	P(300)	0	0					
WELDSUB	904	P(350)	53.73	0		2/26/11	3/2/11		
QC2	1050	P(370)	10	0					
QC2		P(400)	10	0					
WELDMAN	850	P(450)	0	0					
ARC5		P(500)	0	0					
QC2		P(550)	10	0					
WELDMAN	850	P(600)	0	0					
WELDMAN	850	P(650)	7.53	0		3/8/11	3/8/11		
MOVE					6.95				
HTSR	950	P(700)	6.96	0		3/9/11	3/10/11		
HTSR	950	P(750)	6.96	0		3/9/11	3/10/11		
MOVE					10				
VTC2500	416	P(800)	40.32	2.5		3/15/11	3/17/11		
VTC2500	416	P(850)	83.67	6.18		3/25/11	4/5/11		
MOVE					10				
MILLCNC	306	P(900)	24.32	3.63		4/1/11	4/4/11		
MOVE					10				
DEBUR	1000	P(950)	2.9	0		4/5/11	4/5/11		
MOVE					10				
QC2		P(1000)	10	0					
QC2	1050	P(1050)	10	0					
QC2		P(1100)	10	0					
MOVE					10				
SOV3476		P(1150)	62.58	0					

MOVE					10				
QC1	1055	P(1200)	10	0					
MOVE					10				4/12/11

A.2 Production Data Set for TYPICAL Part with Transaction Dates

Work Center	Machine	Operations	Total Time(in Hrs)			First Trx	Last Trx	Issue Date	Manu. Close
			Act Run	Act Setup	Move Time				
PULMAT	PULMTL	P(50)	0	0				1/6/11	
MOVE					10				
BLAST	905	P(60)	5.12	0		2/1/11	2/1/11		
QC2		P(100)	10	0					
MOVE					10				
WELDMAN	850	P(150)	0	0					
WELDSUB	904	P(200)	56.42	13.67		2/7/11	2/13/11		
QC2		P(250)	10	0					
WELDMAN	850	P(300)	0	0					
WELDSUB	904	P(350)	73.15	10.75		2/3/11	2/18/11		
QC2	1050	P(370)	10	0					
QC2		P(400)	10	0					
WELDMAN	850	P(450)	0	0					
ARC5		P(500)	0	0					
QC2		P(550)	10	0					
WELDMAN	850	P(600)	0	0					
WELDMAN	850	P(650)	2.6	2.73		2/22/11	2/22/11		
MOVE					10				
HTSR	950	P(700)	2.33	0		2/23/11	2/23/11		
HTSR	950	P(750)	0	0					
MOVE					10				
VTC2500	418	P(800)	33.22	2.88		2/28/11	3/3/11		
VTC2500	418	P(850)	63.92	3.28		3/9/11	3/14/11		
MOVE					9.37				
MILLCNC	306	R(851)	9.37	2.12		3/15/11	3/15/11		
MOVE					10				
WELDMAN	850	R(856)	7.51	0		3/19/11	3/19/11		
MOVE					10				
MILLCNC	306	R(861)	3.83	2.92		3/21/11	3/22/11		
MOVE					10				

WELDMAN	850	R(866)	4.52	0		3/23/11	3/23/11		
MOVE					10				
LGMILL	312	P(900)	14.88	3.67		3/28/11	3/28/11		
MOVE					10				
VTC2500	416	P(910)	18.3	7.27		4/1/11	4/5/11		
MOVE					10				
DEBUR	1000	P(950)	5.78	0		3/29/11	4/1/11		
MOVE					10				
QC2		R(951)	10	0					
MOVE					10				
HTSR	950	R(956)	12.9	0		4/8/11	4/9/11		
MOVE					10				
BLAST	905	R(961)	10.85	0		4/11/11	4/11/11		
MOVE					10				
DEBUR	1000	R(966)	8.33	0		4/12/11	4/14/11		
DEBUR	1000	R(969)	1.15	0		4/15/11	4/15/11		
MOVE					10				
QC2	1050	R(973)	10	0					
QC2		P(1000)	10	0					
QC2	1050	P(1050)	10	0					
QC2		P(1100)	10	0					
MOVE					10				
SOV3476	3476	P(1150)	62.58	0					
MOVE					10				
QC1	1055	P(1200)	10	0					
MOVE					10				4/26/11

A.3 Production Data Set for WORST Part with Transaction Dates

Work Center	Machine	Operations	Total Time (IN HRS)			First Trx	Last Trx	Issue Date	Manu. Close
			Act Run	Act Setup	Move time				
PULMAT	PULMTL	P(50)	0	0				3/11/11	
MOVE					10				
BLAST	905	P(60)	3.87	0		3/24/11	3/24/11		
QC2		P(100)	6.99	0					
MOVE					10				
WELDMAN	850	P(150)	0	0					
WELDSUB	904	P(200)	56.68	25.87		3/24/11	4/6/11		

QC2		P(250)	0.89	0					
WELDMAN	850	P(300)	0	0					
WELDSUB	904	P(350)	72.68	0		3/29/11	4/7/11		
QC2		P(400)	9.95	0		4/6/11	4/6/11		
WELDMAN	850	P(450)	0	0					
ARC5		P(500)	6.35	0		4/11/11	4/11/11		
QC2		P(550)	10	0					
WELDMAN	850	P(600)	0	0					
WELDMAN	850	P(650)	3.92	0		4/13/11	4/13/11		
MOVE					10				
HTSR	950	P(700)	3.47	0		4/14/11	4/14/11		
HTSR	950	P(750)	3.35	0		4/14/11	4/14/11		
MOVE					10				
WELDMAN	850	R(761)	6.97	0		4/25/11	4/25/11		
MOVE					10				
VTC2500	418	R(781)	6.18	1.93		4/26/11	4/27/11		
MOVE					10				
VTC2500	418	P(800)	37.12	6		4/18/11	5/12/11		
VTC2500	418	P(850)	110.4	10.68		4/27/11	5/16/11		
MOVE					10				
LGMILL	312	P(900)	17.95	2.93		5/23/11	5/24/11		
QC2	1050	R(911)	10	0					
MOVE					10				
HTSR	950	R(921)	0	0					
MOVE					10				
DEBUR	1000	P(950)	8.62	0		5/25/11	5/27/11		
MOVE					10				
QC2		P(1000)	10	0					
MOVE					10				
QC2	1050	P(1050)	10	0					
MOVE					10				
QC2		P(1100)	10	0					
MOVE					10				
LGMILL	312	R(1105)	3.37	0		6/2/11	6/2/11		
MOVE					10				
SOV3700		R(1109)	0	0					
MOVE					10				
QC2	1050	R(1111)	10	0					
MOVE					10				
OSVLK3	LKWD3	R(1112)	0	0					
MOVE					10				

QC2	1050	P(1113)	10	0					
MOVE					10				
WELDMAN	850	R(1115)	79.88	19.32		6/28/11	7/7/11		
WELDMAN	850	R(1119)	15.37	0		7/8/11	7/11/11		
WELDMAN	850	R(1121)	12.85	0		7/12/11	7/13/11		
MOVE					10				
QC2	1050	R(1125)	10	0					
MOVE					10				
VTLBULL	462	R(1127)	27	4.46		7/27/11	8/3/11		
MOVE					10				
VTC2500	418	R(1129)	8.27	4.25		7/22/11	7/22/11		
MOVE					10				
LGMILL	312	R(1133)	5.9	3.3		7/26/11	7/27/11		
MOVE					10				
WELDMAN	850	R(1137)	9.48	0		8/5/11	9/13/11		
MOVE					10				
HTSR	950	R(1139)	8.04	0		8/8/11	8/8/11		
MOVE					10				
BLAST	905	R(1141)	9.85	0		8/11/11	8/12/11		
MOVE					10				
VTLBULL	462	R(1143)	13.28	2.9		8/19/11	8/20/11		
MOVE					10				
QC2	1050	R(1144)	10	0					
MOVE					10				
WELDMAN	850	R(1145)	8.55	0		8/31/11	8/31/11		
MOVE					10				
VTC2500	416	R(1146)	2.33	5.95		9/7/11	9/7/11		
MOVE					10				
DEBUR	1000	R(1151)	12.33	0		9/13/11	9/13/11		
QC2	1050	R(1156)	10	0					
MOVE					10				
HTSR	950	R(1161)	4.37	0		9/15/11	9/15/11		
MOVE					10				
BLAST	905	R(1166)	9.63	0		9/18/11	9/18/11		
MOVE					10				
DEBUR	1000	R(1171)	5.03	0		9/19/11	9/19/11		
MOVE					10				
MILLCNC	314	R(1172)	3.32	5.37		9/20/11	9/21/11		
MOVE					10				
QC2	1050	R(1175)	10	0					
MOVE					10				

SOV3476	3476	R(1181)	62.58	0					
MOVE					10				9/29/11

A.4 Data Set for Operations based Cycle Time Analysis for BEST Part

Day	Operations	Move Time	Queue Time	Act Setup	Act Run	Hold Time	Work Center
0	P(50)	0	0.00	0	0	0.00	PULMAT
28	P(60)	10	574.08	0	9.22	11.64	BLAST
-	P(100)	10	0	0	0	0	WELDMAN
-	P(150)	0	0	0	0	0	WELDMAN
36	P(200)	0	136.02	30.60	139.73	142.57	WELDSUB
-	P(250)	0	0	0	10	0	QC2
-	P(300)	0	0	0	0	0	WELDMAN
51	P(350)	0	0.00	0	53.73	40.57	WELDSUB
-	P(370)	0	0	0	10	0	QC2
-	P(400)	0	0	0	10	0	QC2
-	P(450)	0	0	0	0	0	WELDMAN
-	P(500)	0	0	0	0	0	ARC5
-	P(550)	0	0	0	10	0	QC2
-	P(600)	0	0	0	0	0	WELDMAN
61	P(650)	0	74.30	0	7.53	13.33	WELDMAN
62	P(700)	6.95	0.00	0	6.96	0.00	HTSR
-	P(750)	0	0	0	6.96	0	HTSR
68	P(800)	10	73.44	2.5	40.32	19.76	VTC2500
78	P(850)	0	146.02	6.18	83.67	56.16	VTC2500
85	P(900)	10	0.00	3.63	24.32	45.49	MILLCNC
89	P(950)	10	0.00	0	2.9	7.96	DEBUR
-	P(1000)	10	0	0	10	0	QC2
-	P(1050)	10	0	0	10	0	QC2
-	P(1100)	10	0	0	10	0	QC2
-	P(1150)	10	0	0	62.58	0	SOV3476
96	P(1200)	10	0	0	10	0	QC1

A.5 Data Set for Operations based Cycle Time Analysis for TYPICAL Part

Day	Operations	Move Time	Queue Time	Act Setup	Act Run	Hold Time	Work Center
0	P(50)	0	0	0	0	0	PULMAT
26	P(60)	10	531.84	0	5.12	15.72	BLAST
-	P(100)	0	0	0	10	0	QC2
-	P(150)	10	0	0	0	0	WELDMAN
28	P(350)	0	0.86	10.75	73.15	93.84	WELDSUB
32	P(200)	0	0.00	13.67	56.42	75.93	WELDSUB
-	P(250)	0	0	0	10	0	QC2
-	P(300)	0	0	0	0	0	WELDMAN
-	P(370)	0	0	0	10	0	QC2
-	P(400)	0	0	0	10	0	QC2
-	P(450)	0	0	0	0	0	WELDMAN
-	P(500)	0	0	0	0	0	ARC5
-	P(550)	0	0	0	10	0	QC2
-	P(600)	0	0	0	0	0	WELDMAN
47	P(650)	0	32.58	2.73	2.6	15.53	WELDMAN
48	P(700)	10	0.00	0	2.33	8.53	HTSR
-	P(750)	0	0	0	0	0	HTSR
53	P(800)	10	73.44	2.88	33.22	47.34	VTC2500
62	P(850)	0	104.30	3.28	63.92	57.96	VTC2500
68	R(851)	9.37	0.00	2.12	9.37	0.00	MILLCNC
72	R(856)	10	52.58	0	7.51	13.35	WELDMAN
74	R(861)	10	10.86	2.92	3.83	34.97	MILLCNC
76	R(866)	10	0.00	0	4.52	6.34	WELDMAN
81	P(900)	10	73.44	3.67	14.88	2.31	LGMILL
82	P(950)	10	0.00	0	5.78	67.66	DEBUR
85	P(910)	10	0.00	7.27	18.3	47.87	VTC2500
-	R(951)	10	0	0	10	0	QC2
92	R(956)	10	11.72	0	12.9	28.82	HTSR
95	R(961)	10	10.86	0	10.85	10.01	BLAST
96	R(966)	10	0.00	0	8.33	54.25	DEBUR

99	R(969)	0	0.00	0	1.15	19.71	DEBUR
-	R(973)	10	0	0	10	0	QC2
-	P(1000)	10	0	0	10	0	QC2
-	P(1050)	10	0	0	10	0	QC2
-	P(1100)	10	0	0	10	0	QC2
-	P(1150)	10	0	0	62.58	0	SOV3476
110	P(1200)	10	0	0	10	0	QC1

A.6 Data Set for Operations based Cycle Time Analysis for WORST Part

Day	Operations	Move time	Queue Time	Act Setup	Act Run	Hold Time	Work Center
0	P(50)	0	0.00	0	0	0.00	PULMAT
13	P(60)	10	261.14	0	3.87	0.00	BLAST
13	P(100)	0	0.00	0	6.99	0.00	QC2
13	P(150)	10	0	0	0	0	WELDMAN
13	P(200)	0	0.00	25.87	56.68	0.00	WELDSUB
-	P(250)	0	0	0	0.89	0	QC2
-	P(300)	0	0	0	0	0	WELDMAN
18	P(350)	0	0.00	0	72.68	94.20	WELDSUB
26	P(400)	0	0.00	0	9.95	10.91	QC2
-	P(450)	0	0	0	0	0	WELDMAN
31	P(500)	0	62.58	0	6.35	14.51	ARC5
-	P(550)	0	0	0	10	0	QC2
-	P(600)	0	0	0	0	0	WELDMAN
33	P(650)	0	10.86	0	3.92	6.94	WELDMAN
34	P(700)	10	0.00	0	3.47	14.04	HTSR
-	P(750)	0	0	0	3.35	0	HTSR
38	P(800)	10	52.58	6	37.12	92.90	VTC2500
45	R(761)	10	0.00	0	6.97	13.89	WELDMAN
46	R(781)	10	0.00	1.93	6.18	23.61	VTC2500
47	P(850)	0	0.00	10.68	110.4	296.12	VTC2500
73	P(900)	10	115.16	2.93	17.95	20.84	LGMILL

-	R(911)	0	0	0	10	0	QC2
-	R(921)	10	0	0	0	0	HTSR
75	P(950)	10	0.00	0	8.62	32.58	DEBUR
-	P(1000)	10	0	0	10	0	QC2
-	P(1050)	10	0	0	10	0	QC2
-	P(1100)	10	0	0	10	0	QC2
83	R(1105)	10	34.30	0	3.37	17.49	LGMILL
-	R(1109)	10	0	0	0	0	SOV3700
-	R(1111)	10	0	0	10	0	QC2
-	R(1112)	10	0	0	0	0	OSVLK3
-	P(1113)	10	0	0	10	0	QC2
109	R(1115)	10	451.50	19.32	79.88	109.40	WELDMAN
119	R(1119)	0	0.00	0	15.37	68.07	WELDMAN
123	R(1121)	0	0.00	0	12.85	28.87	WELDMAN
-	R(1125)	10	0	0	10	0	QC2
133	R(1129)	10	136.88	4.25	8.27	8.34	VTC2500
137	R(1133)	10	52.58	3.3	5.9	11.66	LGMILL
138	R(1127)	10	0.00	4.46	27	125.42	VTLBULL
147	R(1137)	10	10.86	0	9.48	157.40	WELDMAN
150	R(1139)	10	0.00	0	8.04	2.82	HTSR
153	R(1141)	10	31.72	0	9.85	31.87	BLAST
161	R(1143)	10	115.16	2.9	13.28	25.54	VTLBULL
-	R(1144)	10	0	0	10	0	QC2
173	R(1145)	10	178.60	0	8.55	12.31	WELDMAN
180	R(1146)	10	115.16	5.95	2.33	12.58	VTC2500
186	R(1151)	10	0.00	0	12.33	8.53	DEBUR
-	R(1156)	0	0	0	10	0	QC2
188	R(1161)	10	0.86	0	4.37	16.49	HTSR
191	R(1166)	10	31.72	0	9.63	11.23	BLAST
192	R(1171)	10	0.00	0	5.03	5.83	DEBUR
193	R(1172)	10	0.00	5.37	3.32	23.03	MILLCNC
-	R(1175)	10	0	0	10	0	QC2
202	R(1181)	10	0	0	62.58	0	SOV3476

Appendix B: Rework Data Set

B.1 Rework Data with Transaction Dates and RC Codes

NCR#	RC	RC Desc	Insp Date	WO	Act Run	Act Setup	Rework LT	First Trx	Last Trx
74202	25	OSV, machining	1/12/2011	3148183	37.95001	2.98333	5	1/19/2011	1/24/2011
74202	25	OSV, machining	1/12/2011	3148183	4.19167	0	0	1/25/2011	1/25/2011
74281	18	Tooling, wrong tool issued or tool set wrong	1/23/2011	3167821	1.01667	0	0	1/26/2011	1/26/2011
74285	8	Weld, inlay	1/24/2011	3163113	3.11667	0	21	1/4/2011	1/25/2011
74285	8	Weld, inlay	1/24/2011	3163113	1.21667	0	0	1/25/2011	1/25/2011
74285	8	Weld, inlay	1/24/2011	3163113	34	5.81667	11	2/1/2011	2/12/2011
74293	42	Weld, fabrication	1/27/2011	3136076	24.94166	0	157	2/14/2011	7/21/2011
74293	42	Weld, fabrication	1/27/2011	3136076	110.59166	0	13	2/16/2011	3/1/2011
74293	42	Weld, fabrication	1/27/2011	3136076	18.58334	3.85	104	3/3/2011	6/15/2011
74293	42	Weld, fabrication	1/27/2011	3136076	10.85	1.63334	1	3/3/2011	3/4/2011
74293	42	Weld, fabrication	1/27/2011	3136076	2.76667	0	0	3/11/2011	3/11/2011
75485	39	Operator error, missed dimension	1/4/2011	3136076	1.4	0	0	1/5/2011	1/5/2011
75485	39	Operator error, missed dimension	1/4/2011	3136076	3.81667	0	0	1/15/2011	1/15/2011
75485	39	Operator error, missed dimension	1/4/2011	3136076	1.35	3.73333	1	1/18/2011	1/19/2011
75485	39	Operator error, missed dimension	1/4/2011	3136076	0	1.65	0	1/21/2011	1/21/2011
75487	73	Eng, Design error	1/5/2011	3165456	9.28334	4.59444	1	1/6/2011	1/7/2011
75487	73	Eng, Design error	1/5/2011	3165456	6.76667	0	0	1/8/2011	1/8/2011
75487	73	Eng, Design error	1/5/2011	3165456	2.4	7.06666	7	1/13/2011	1/20/2011
75487	73	Eng, Design error	1/5/2011	3165456	2.16667	0.7	0	1/17/2011	1/17/2011
80460	64	QC, missed inspections	1/26/2011	3167823	8.83333	1.28333	1	1/26/2011	1/27/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	3.03333	0	40	1/17/2011	2/26/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	8.38334	2.58333	2	2/28/2011	3/2/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	5.4	2	50	1/26/2011	3/17/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	14.17917	0	1	3/8/2011	3/9/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	10.94166	0	1	3/10/2011	3/11/2011
80523	39	Operator error, missed dimension	2/24/2011	3163113	12.36667	0	0	3/11/2011	3/11/2011
80527	2	Process problem	2/24/2011	3165456	3.13333	2.85	170	1/25/2011	7/14/2011
80532	39	Operator error, missed dimension	2/25/2011	3148183	4.46667	4.26667	0	3/4/2011	3/4/2011
80532	39	Operator error, missed dimension	2/25/2011	3148183	200.73334	6.13333	19	3/16/2011	4/4/2011
80532	39	Operator error, missed dimension	2/25/2011	3148183	32.05	9.31666	54	3/17/2011	5/10/2011
80536	11	Deburred incorrectly	2/26/2011	3167821	20	0	0	3/1/2011	3/1/2011
80577	25	OSV, machining	3/5/2011	3135032	2.8	0	0	9/3/2011	9/3/2011
80621	8	Weld, inlay	3/12/2011	3163113	3.98333	0	202	3/15/2011	10/3/2011

80621	8	Weld, inlay	3/12/2011	3163113	4.41666	4.21667	67	3/18/2011	5/24/2011
80621	8	Weld, inlay	3/12/2011	3163113	22.88333	5.5	69	3/18/2011	5/26/2011
80621	8	Weld, inlay	3/12/2011	3163113	10.02222	0	0	3/23/2011	3/23/2011
80621	8	Weld, inlay	3/12/2011	3163113	14.10833	0	3	3/23/2011	3/26/2011
80633	42	Weld, fabrication	3/14/2011	3136076	2.03333	1.01667	154	3/24/2011	8/25/2011
80633	42	Weld, fabrication	3/14/2011	3136076	38.55	3.5	82	4/1/2011	6/22/2011
80633	42	Weld, fabrication	3/14/2011	3136076	47.56666	1.96667	148	4/14/2011	9/9/2011
80654	69	ECN (dwg or bom revised)	3/17/2011	3171311	0.65	3.91667	117	3/19/2011	7/14/2011
80659	9	OSV, bad material	3/18/2011	3159984	7.03333	0	0	4/13/2011	4/13/2011
82242	2	Process problem	3/29/2011	3135025	1.03333	0	184	1/12/2011	7/15/2011
82242	2	Process problem	3/29/2011	3135025	1.06667	0	0	4/18/2011	4/18/2011
82244	36	Operator did not follow router instructions	3/29/2011	3153671	11.01667	0	5	3/30/2011	4/4/2011
82244	36	Operator did not follow router instructions	3/29/2011	3153671	2.03333	0	0	4/8/2011	4/8/2011
82244	36	Operator did not follow router instructions	3/29/2011	3153671	14.90833	1.1	5	4/1/2011	4/6/2011
82260	25	OSV, machining	4/1/2011	3177387	2.2	0	203	1/26/2011	8/17/2011
82260	25	OSV, machining	4/1/2011	3177387	35.11666	0	159	4/13/2011	9/19/2011
82260	25	OSV, machining	4/1/2011	3177387	12.2025	0	98	4/19/2011	7/26/2011
82344	29	Machining, Incorrect setup by operator	4/14/2011	3167399	0	1	0	5/4/2011	5/4/2011
82438	42	Weld, fabrication	5/2/2011	3156056	1.5	0	0	6/9/2011	6/9/2011
82438	42	Weld, fabrication	5/2/2011	3156056	73.48332	6.3	6	6/9/2011	6/15/2011
82439	2	Process problem	5/2/2011	3177387	26.45	6.08333	5	5/13/2011	5/18/2011
82439	2	Process problem	5/2/2011	3177387	4.01667	0	0	8/1/2011	8/1/2011
82439	2	Process problem	5/2/2011	3177387	6.65	0	0	8/3/2011	8/3/2011
82515	43	Handling damage	5/12/2011	3165848	3.26667	0	0	5/17/2011	5/17/2011
82688	42	Weld, fabrication	5/30/2011	3171073	3.36667	0	0	6/2/2011	6/2/2011
82688	42	Weld, fabrication	5/30/2011	3171073	79.88333	19.31667	9	6/28/2011	7/7/2011
82688	42	Weld, fabrication	5/30/2011	3171073	15.36667	0	3	7/8/2011	7/11/2011
82688	42	Weld, fabrication	5/30/2011	3171073	12.85	0	28	7/12/2011	8/9/2011
82688	42	Weld, fabrication	5/30/2011	3171073	8.26667	4.25	0	7/22/2011	7/22/2011
82688	42	Weld, fabrication	5/30/2011	3171073	5.9	3.3	1	7/26/2011	7/27/2011
82700	43	Handling damage	6/1/2011	3180706	2.4	0	98	4/19/2011	7/26/2011
82700	43	Handling damage	6/1/2011	3180706	5.15	0	41	6/9/2011	7/20/2011
82768	43	Handling damage	6/10/2011	3180706	7.3	0	1	7/11/2011	7/12/2011
82768	43	Handling damage	6/10/2011	3180706	3.15	0	0	7/18/2011	7/18/2011
82779	43	Handling damage	6/13/2011	3165945	3.31667	1.28333	202	3/15/2011	10/3/2011
82779	43	Handling damage	6/13/2011	3165945	2.2	0	200	3/21/2011	10/7/2011
82784	42	Weld, fabrication	6/13/2011	3156890	36.77501	0	122	2/15/2011	6/17/2011
82784	42	Weld, fabrication	6/13/2011	3156890	7	0	124	2/16/2011	6/20/2011
82784	42	Weld, fabrication	6/13/2011	3156890	1.79167	2.275	2	6/18/2011	6/20/2011
82847	34	Machine malfuntion	6/25/2011	3156057	3.75	0	173	4/20/2011	10/10/2011
82847	34	Machine malfuntion	6/25/2011	3156057	3.3	0	269	1/12/2011	10/8/2011

82910	42	Weld, fabrication	7/15/2011	3171073	26.99999	4.45834	7	7/27/2011	8/3/2011
82953	42	Weld, fabrication	7/1/2011	3166230	33.26667	0	2	7/12/2011	7/14/2011
82953	42	Weld, fabrication	7/1/2011	3166230	1.46667	4.76667	0	7/18/2011	7/18/2011
82953	42	Weld, fabrication	7/1/2011	3166230	6.16583	0	0	7/26/2011	7/26/2011
82953	42	Weld, fabrication	7/1/2011	3166230	9.75	0	0	7/29/2011	7/29/2011
82976	42	Weld, fabrication	7/6/2011	3156890	5.78333	2.56667	1	7/7/2011	7/8/2011
82976	42	Weld, fabrication	7/6/2011	3156890	0.65	0	0	7/11/2011	7/11/2011
82985	6	Stamped incorrectly	7/7/2011	3176808	0.46667	0	190	1/10/2011	7/19/2011
83099	48	Assembly, damage	7/27/2011	3171101	20.21667	0	1	7/27/2011	7/28/2011
83099	48	Assembly, damage	7/27/2011	3171101	0.98333	0	0	7/28/2011	7/28/2011
83099	48	Assembly, damage	7/27/2011	3171101	30.56666	0	1	8/1/2011	8/2/2011
83099	48	Assembly, damage	7/27/2011	3171101	1.16667	0	0	8/2/2011	8/2/2011
83127	48	Assembly, damage	8/1/2011	3180706	4.18333	0.96666	3	8/5/2011	8/8/2011
83127	48	Assembly, damage	8/1/2011	3180706	2.61667	0	0	8/8/2011	8/8/2011
83206			8/11/2011	3171101	5.68333	0	1	8/12/2011	8/13/2011
83231	2	Process problem	8/15/2011	3171101	20.33332	5.35	2	8/17/2011	8/19/2011
83833	18	Tooling, wrong tool issued or tool set wrong	1/14/2011	3167821	14.71667	0	40	1/17/2011	2/26/2011
83843	39	Operator error, missed dimension	1/21/2011	3165456	7.48333	0	210	2/3/2011	9/1/2011
83843	39	Operator error, missed dimension	1/21/2011	3165456	2.05	3.7	0	2/7/2011	2/7/2011
83845	87	Tooling, tool broke	1/22/2011	3164023	6.28333	0	0	2/1/2011	2/1/2011
83845	87	Tooling, tool broke	1/22/2011	3164023	3.65	1.66667	0	2/5/2011	2/5/2011
83845	87	Tooling, tool broke	1/22/2011	3164023	3.8	0	0	2/7/2011	2/7/2011
83845	87	Tooling, tool broke	1/22/2011	3164023	10.61667	0	0	2/10/2011	2/10/2011
83866	48	Assembly, damage	2/2/2011	3167821	34.41667	13.00001	7	2/18/2011	2/25/2011
83875	43	Handling damage	2/14/2011	3164023	0.68333	3.21667	122	2/15/2011	6/17/2011
83875	43	Handling damage	2/14/2011	3164023	7.35	0	124	2/16/2011	6/20/2011
83875	43	Handling damage	2/14/2011	3164023	2.96667	3.93333	131	2/16/2011	6/27/2011
83875	43	Handling damage	2/14/2011	3164023	1.21556	0	134	2/16/2011	6/30/2011
83875	43	Handling damage	2/14/2011	3164023	10	0	0	2/19/2011	2/19/2011
83877	21	Programming, error in program	2/15/2011	3163118	5.55	1.73333	148	3/7/2011	8/2/2011
83877	21	Programming, error in program	2/15/2011	3163118	8.38972	0	50	1/26/2011	3/17/2011
83877	21	Programming, error in program	2/15/2011	3163118	20.075	0	50	1/28/2011	3/19/2011
83893	39	Operator error, missed dimension	2/23/2011	3153671	18.25	19.15833	214	2/10/2011	9/12/2011
83893	39	Operator error, missed dimension	2/23/2011	3153671	4.91666	2.2	88	3/14/2011	6/10/2011
83893	39	Operator error, missed dimension	2/23/2011	3153671	11.61666	5.83333	122	3/18/2011	7/18/2011
83893	39	Operator error, missed dimension	2/23/2011	3153671	7.31667	0	0	4/9/2011	4/9/2011
83893	39	Operator error, missed dimension	2/23/2011	3153671	8.1	0	127	4/13/2011	8/18/2011
83899	8	Weld, inlay	2/26/2011	3161169	3.81667	0	8	3/7/2011	3/15/2011
83899	8	Weld, inlay	2/26/2011	3161169	7.01666	2.9	140	3/17/2011	8/4/2011
83909	64	QC, missed inspections	3/1/2011	3159977	9.36667	2.11667	202	3/15/2011	10/3/2011
83909	64	QC, missed inspections	3/1/2011	3159977	7.50834	0	0	3/19/2011	3/19/2011

83909	64	QC, missed inspections	3/1/2011	3159977	3.83333	2.91667	200	3/21/2011	10/7/2011
83909	64	QC, missed inspections	3/1/2011	3159977	4.51667	0	3	3/23/2011	3/26/2011
83909	64	QC, missed inspections	3/1/2011	3159977	12.89556	0	1	4/8/2011	4/9/2011
83909	64	QC, missed inspections	3/1/2011	3159977	10.85	0	173	4/11/2011	10/1/2011
83909	64	QC, missed inspections	3/1/2011	3159977	8.33333	0	128	4/12/2011	8/18/2011
83940	8	Weld, inlay	3/18/2011	3161169	10.91666	0	140	3/21/2011	8/8/2011
83940	8	Weld, inlay	3/18/2011	3161169	2.88334	4.68333	1	3/22/2011	3/23/2011
83970	8	Weld, inlay	3/30/2011	3165945	11.38334	0	190	1/10/2011	7/19/2011
83970	8	Weld, inlay	3/30/2011	3165945	7.06667	1.01667	1	4/13/2011	4/14/2011
83970	8	Weld, inlay	3/30/2011	3165945	6.925	0	9	4/18/2011	4/27/2011
83970	8	Weld, inlay	3/30/2011	3165945	18.41667	2.7	13	4/27/2011	5/10/2011
83970	8	Weld, inlay	3/30/2011	3165945	3.95416	0	214	2/10/2011	9/12/2011
83970	8	Weld, inlay	3/30/2011	3165945	4.85	0	88	3/14/2011	6/10/2011
84005	1	Machining, tapping	4/14/2011	3159977	1.15	0	0	4/15/2011	4/15/2011
84010	39		4/18/2011	3148183	4.06667	9.9	0	4/25/2011	4/25/2011
84010	39		4/18/2011	3148183	36.90832	3.68333	6	5/5/2011	5/11/2011
84016	43	Handling damage	4/19/2011	3153671	5.86667	10.73334	173	4/20/2011	10/10/2011
84017	8	Weld, inlay	4/20/2011	3171073	6.96667	0	9	4/25/2011	5/4/2011
84017	8	Weld, inlay	4/20/2011	3171073	6.18334	1.93334	1	4/26/2011	4/27/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	1.31667	0.5	118	1/6/2011	5/4/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	0.85	0	190	1/10/2011	7/19/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	3.975	0	65	5/18/2011	7/22/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	1.08333	0	0	5/20/2011	5/20/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	2.57972	0	67	3/18/2011	5/24/2011
84018	41	Weld, non-inlay	4/20/2011	3156693	1.36667	0	69	3/18/2011	5/26/2011
84025	8	Weld, inlay	4/25/2011	3171102	19.06667	0	9	4/25/2011	5/4/2011
84025	8	Weld, inlay	4/25/2011	3171102	8.18333	3.45	1	5/16/2011	5/17/2011
84025	8	Weld, inlay	4/25/2011	3171102	22.33333	2.15	1	5/20/2011	5/21/2011
84025	8	Weld, inlay	4/25/2011	3171102	13.18333	0.26667	2	6/2/2011	6/4/2011
84025	8	Weld, inlay	4/25/2011	3171102	6.16389	0	104	3/3/2011	6/15/2011
84025	8	Weld, inlay	4/25/2011	3171102	8.41666	0	0	6/21/2011	6/21/2011
84025	8	Weld, inlay	4/25/2011	3171102	5.88333	0	82	4/1/2011	6/22/2011
84302	2	Process problem	6/30/2011	3183654	6.63333	0	203	1/26/2011	8/17/2011
84318	43	Handling damage	7/11/2011	3163111	14.46667	2.33333	119	3/16/2011	7/13/2011
84400	2	Process problem	8/16/2011	3163112	3.08333	0	203	1/26/2011	8/17/2011
84400	2	Process problem	8/16/2011	3163112	50.43333	0	3	8/20/2011	8/23/2011
84400	2	Process problem	8/16/2011	3163112	18.55834	0	1	9/1/2011	9/2/2011
84410	9	OSV, bad material	5/9/2011	3180506	2.81667	3.15	159	4/13/2011	9/19/2011
84410	9	OSV, bad material	5/9/2011	3180506	10.03333	3.48333	22	7/25/2011	8/16/2011
84410	9	OSV, bad material	5/9/2011	3180506	1.80833	0	98	4/19/2011	7/26/2011
84437	2	Process problem	2/23/2011	3175477	6.34999	0	273	1/4/2011	10/4/2011

84490	48	Assembly, damage	3/29/2011	3167820	22.41666	0	1	4/2/2011	4/3/2011
84497	48	Assembly, damage	4/3/2011	3177938	3.56667	0	0	4/13/2011	4/13/2011
85328	2	Process problem	10/6/2011	3170530	14.8	0	269	1/12/2011	10/8/2011
90659	8	Weld, inlay	7/7/2011	3156056	29.56667	0	170	1/25/2011	7/14/2011
90659	8	Weld, inlay	7/7/2011	3156056	16.76666	4.55	154	3/24/2011	8/25/2011
85419	42	Weld, fabrication	9/19/2011	3156056	0.96667	4.51667	0	10/1/2011	10/1/2011
85419	42	Weld, fabrication	9/19/2011	3156056	9.33333	0	0	10/6/2011	10/6/2011
86637	43	Handling damage	8/10/2011	3186239	0.66667	0	203	1/26/2011	8/17/2011
86653	43	Handling damage	8/15/2011	3186344	2.6	0	273	1/4/2011	10/4/2011
87121	29	Machining, Incorrect setup by operator	9/7/2011	3184867	20.51667	3.75	80	6/22/2011	9/10/2011
87122	2	Process problem	9/7/2011	3187633	2.61666	0	1	9/19/2011	9/20/2011
87122	2	Process problem	9/7/2011	3187633	1.96666	0	0	9/20/2011	9/20/2011
87242	43	Handling damage	5/11/2011	3180706	5.92499	0	203	1/26/2011	8/17/2011
87283	25	OSV, machining	6/9/2011	3165847	9.76667	4.76667	159	4/13/2011	9/19/2011
87313	43	Handling damage	4/4/2011	3167820	32.73334	0	1	4/5/2011	4/6/2011
87379	48	Assembly, damage	7/1/2011	3171101	16.63334	1.83333	258	1/20/2011	10/5/2011
87379	48	Assembly, damage	7/1/2011	3171101	23.60833	0	1	7/13/2011	7/14/2011
87395	48	Assembly, damage	8/5/2011	3171101	5.05	0	0	8/6/2011	8/6/2011
87395	48	Assembly, damage	8/5/2011	3171101	6.21667	4.05	140	3/21/2011	8/8/2011
87395	48	Assembly, damage	8/5/2011	3171101	12.79999	0	15	9/6/2011	9/21/2011
87424	2	Process problem	8/28/2011	3186938	2.29166	0	203	2/8/2011	8/30/2011
90520	8	Weld, inlay	5/11/2011	3148183	14.13333	0	1	6/1/2011	6/2/2011
90520	8	Weld, inlay	5/11/2011	3148183	8.7	0	1	6/3/2011	6/4/2011
90520	8	Weld, inlay	5/11/2011	3148183	25.48334	1.35	5	6/15/2011	6/20/2011
90520	8	Weld, inlay	5/11/2011	3148183	5.23333	0	0	6/22/2011	6/22/2011
90536	8	Weld, inlay	5/20/2011	3172077	4.3	0	0	6/3/2011	6/3/2011
90536	8	Weld, inlay	5/20/2011	3172077	7.55	0	0	6/4/2011	6/4/2011
90536	8	Weld, inlay	5/20/2011	3172077	7.96667	4.36667	1	6/9/2011	6/10/2011
90537	41	Weld, non-inlay	5/18/2011	3166230	7.93333	0	0	5/31/2011	5/31/2011
90537	41	Weld, non-inlay	5/18/2011	3166230	4.155	0	1	6/1/2011	6/2/2011
90537	41	Weld, non-inlay	5/18/2011	3166230	26.825	0	3	6/5/2011	6/8/2011
90537	41	Weld, non-inlay	5/18/2011	3166230	27.4	0	2	6/13/2011	6/15/2011
90591	8	Weld, inlay	6/10/2011	3172077	2.09611	0	65	5/18/2011	7/22/2011
90591	8	Weld, inlay	6/10/2011	3172077	15.8	0	4	7/21/2011	7/25/2011
90597	8	Weld, inlay	6/14/2011	3170530	7.52917	0	173	4/11/2011	10/1/2011
90597	8	Weld, inlay	6/14/2011	3170530	7.45	0	1	10/2/2011	10/3/2011
90597	8	Weld, inlay	6/14/2011	3170530	3.88333	0	0	10/4/2011	10/4/2011
90599	8	Weld, inlay	6/14/2011	3166230	4.36667	0	0	6/22/2011	6/22/2011
90601	64	QC, missed inspections	6/14/2011	3172077	13.475	0	42	6/17/2011	7/29/2011
90601	64	QC, missed inspections	6/14/2011	3172077	5.85	2.36667	148	3/7/2011	8/2/2011
90601	64	QC, missed inspections	6/14/2011	3172077	19.48333	0	1	7/7/2011	7/8/2011

90601	64	QC, missed inspections	6/14/2011	3172077	21.01667	1.85	1	7/13/2011	7/14/2011
90607	41	Weld, non-inlay	6/15/2011	3156890	75.51667	9.3	131	2/16/2011	6/27/2011
90607	41	Weld, non-inlay	6/15/2011	3156890	16.1	1.06667	134	2/16/2011	6/30/2011
90607	41	Weld, non-inlay	6/15/2011	3156890	1.41611	0	0	7/12/2011	7/12/2011
90607	41	Weld, non-inlay	6/15/2011	3156890	30.14167	0	1	7/14/2011	7/15/2011
90607	41	Weld, non-inlay	6/15/2011	3156890	29.31668	3.2	2	7/18/2011	7/20/2011
90628	42	Weld, fabrication	6/23/2011	3148183	12.83334	0	265	1/15/2011	10/7/2011
90628	42	Weld, fabrication	6/23/2011	3148183	15.51666	4.95	80	6/22/2011	9/10/2011
90631	25	OSV, machining	6/24/2011	3165847	6.03333	0	0	6/24/2011	6/24/2011
90631	25	OSV, machining	6/24/2011	3165847	12.35833	0	2	8/18/2011	8/20/2011
90648	8	Weld, inlay	7/1/2011	3167399	5.05	0	117	3/19/2011	7/14/2011
90648	8	Weld, inlay	7/1/2011	3167399	6.00278	0	42	6/17/2011	7/29/2011
90648	8	Weld, inlay	7/1/2011	3167399	9.24999	0	148	3/7/2011	8/2/2011
90648	8	Weld, inlay	7/1/2011	3167399	8.46667	0	7	8/3/2011	8/10/2011
85419	42	Weld, fabrication	9/19/2011	3156056	22.80833	3.91667	3	10/3/2011	10/6/2011
85419	42	Weld, fabrication	9/19/2011	3156056	7.56667	0	0	10/5/2011	10/5/2011
90663	8	Weld, inlay	7/9/2011	3164401	5	4.36667	38	6/3/2011	7/11/2011
90663	8	Weld, inlay	7/9/2011	3164401	22.51666	20.06666	122	3/18/2011	7/18/2011
90663	8	Weld, inlay	7/9/2011	3164401	5.55	0	0	7/18/2011	7/18/2011
90663	8	Weld, inlay	7/9/2011	3164401	19.74999	3.5	7	7/25/2011	8/1/2011
90663	8	Weld, inlay	7/9/2011	3164401	5.48333	0	0	7/23/2011	7/23/2011
90663	8	Weld, inlay	7/9/2011	3164401	12.06333	0	173	4/11/2011	10/1/2011
90663	8	Weld, inlay	7/9/2011	3164401	7.71667	0	128	4/12/2011	8/18/2011
90663	8	Weld, inlay	7/9/2011	3164401	6.125	0	127	4/13/2011	8/18/2011
90684	41	Weld, non-inlay	7/20/2011	3156890	25.83334	2.93333	2	7/20/2011	7/22/2011
90684	41	Weld, non-inlay	7/20/2011	3156890	23.36667	0	3	7/21/2011	7/24/2011
90684	41	Weld, non-inlay	7/20/2011	3156890	482.6167	3.25	29	7/25/2011	8/23/2011
90684	41	Weld, non-inlay	7/20/2011	3156890	12.91666	0	1	8/20/2011	8/21/2011
90684	41	Weld, non-inlay	7/20/2011	3156890	41.76668	0	2	8/24/2011	8/26/2011
90706	42	Weld, fabrication	8/1/2011	3176397	9.03333	0	25	8/2/2011	8/27/2011
90706	42	Weld, fabrication	8/1/2011	3176397	13.51667	3.93333	31	8/9/2011	9/9/2011
90708	41	Weld, non-inlay	8/2/2011	3166230	7.43333	0	269	1/12/2011	10/8/2011
90708	41	Weld, non-inlay	8/2/2011	3166230	7.45	2.46667	28	7/12/2011	8/9/2011
90708	41	Weld, non-inlay	8/2/2011	3166230	8.38805	0	2	8/20/2011	8/22/2011
90708	41	Weld, non-inlay	8/2/2011	3166230	5.5	0	0	8/22/2011	8/22/2011
90708	41	Weld, non-inlay	8/2/2011	3166230	2.76667	0	0	8/22/2011	8/22/2011
90709	41	Weld, non-inlay	8/3/2011	3171073	9.48333	0	39	8/5/2011	9/13/2011
90709	41	Weld, non-inlay	8/3/2011	3171073	8.03472	0	0	8/8/2011	8/8/2011
90709	41	Weld, non-inlay	8/3/2011	3171073	9.85	0	1	8/11/2011	8/12/2011
90709	41	Weld, non-inlay	8/3/2011	3171073	13.28334	2.9	1	8/19/2011	8/20/2011
90740	41	Weld, non-inlay	8/10/2011	3176397	12.93333	0	30	8/10/2011	9/9/2011

90740	41	Weld, non-inlay	8/10/2011	3176397	37.61667	1.66667	13	8/17/2011	8/30/2011
90740	41	Weld, non-inlay	8/10/2011	3176397	3.41667	3.75	15	9/7/2011	9/22/2011
90757	41	Weld, non-inlay	8/17/2011	3170530	7.28333	0	210	2/3/2011	9/1/2011
90757	41	Weld, non-inlay	8/17/2011	3170530	7.66667	2.68333	214	2/10/2011	9/12/2011
90764	43	Handling damage	8/19/2011	3164401	1.01667	0	26	8/19/2011	9/14/2011
90766	42	Weld, fabrication	8/20/2011	3171073	8.55	0	0	8/31/2011	8/31/2011
90766	42	Weld, fabrication	8/20/2011	3171073	2.33333	5.95	0	9/7/2011	9/7/2011
90766	42	Weld, fabrication	8/20/2011	3171073	12.325	0	0	9/13/2011	9/13/2011
90766	42	Weld, fabrication	8/20/2011	3171073	4.3725	0	0	9/15/2011	9/15/2011
90766	42	Weld, fabrication	8/20/2011	3171073	9.63333	0	0	9/18/2011	9/18/2011
90766	42	Weld, fabrication	8/20/2011	3171073	5.03333	0	0	9/19/2011	9/19/2011
90768	2	Process problem	8/19/2011	3171101	34.48334	0	26	8/19/2011	9/14/2011
90768	2	Process problem	8/19/2011	3171101	45.85832	0	28	9/10/2011	10/8/2011
90774	42	Weld, fabrication	8/22/2011	3179916	8.98333	0	25	8/2/2011	8/27/2011
90774	42	Weld, fabrication	8/22/2011	3179916	10.16667	2.48333	31	8/9/2011	9/9/2011
90790	42	Weld, fabrication	8/26/2011	3156890	20.70001	1.05	2	8/30/2011	9/1/2011
90790	42	Weld, fabrication	8/26/2011	3156890	7.61666	0	1	8/29/2011	8/30/2011
90790	42	Weld, fabrication	8/26/2011	3156890	14.33333	0	0	9/1/2011	9/1/2011
90790	42	Weld, fabrication	8/26/2011	3156890	14.00001	0	1	9/21/2011	9/22/2011
90792	42	Weld, fabrication	8/26/2011	3181534	6.31667	0	0	8/29/2011	8/29/2011
90800	41	Weld, non-inlay	8/30/2011	3179916	6.875	0	30	8/10/2011	9/9/2011
90800	41	Weld, non-inlay	8/30/2011	3179916	45.53334	0	15	9/7/2011	9/22/2011
90800	41	Weld, non-inlay	8/30/2011	3179916	12.35	2.56667	1	10/6/2011	10/7/2011
90816	86	Tooling, fixture moved	9/3/2011	3156890	72.73332	11.2	11	9/2/2011	9/13/2011
90816	86	Tooling, fixture moved	9/3/2011	3156890	19.4	7.4	9	9/7/2011	9/16/2011
90816	86	Tooling, fixture moved	9/3/2011	3156890	3.33333	0	0	7/5/2011	7/5/2011
90816	86	Tooling, fixture moved	9/3/2011	3156890	15.21111	0	0	9/19/2011	9/19/2011
90816	86	Tooling, fixture moved	9/3/2011	3156890	7.78334	0	1	9/20/2011	9/21/2011
90835	41	Weld, non-inlay	9/14/2011	3170530	6.01666	0	202	3/15/2011	10/3/2011
90835	41	Weld, non-inlay	9/14/2011	3170530	1.88333	0	200	3/21/2011	10/7/2011
90852	39	Operator error, missed dimension	9/20/2011	3171073	3.31667	5.36667	1	9/20/2011	9/21/2011
90857	2	Process problem	9/21/2011	3187633	4.55	1.48333	273	1/4/2011	10/4/2011
90858	41	Weld, non-inlay	9/22/2011	3170535	18.1	0	202	3/15/2011	10/3/2011
90858	41	Weld, non-inlay	9/22/2011	3170535	8.85	2.76667	9	9/27/2011	10/6/2011
90858	41	Weld, non-inlay	9/22/2011	3170535	9.2	0	200	3/21/2011	10/7/2011
90862	41	Weld, non-inlay	9/22/2011	3156890	5.18333	0	0	9/26/2011	9/26/2011
90862	41	Weld, non-inlay	9/22/2011	3156890	24.76667	0	7	9/24/2011	10/1/2011
90862	41	Weld, non-inlay	9/22/2011	3156890	5.33333	0	0	10/10/2011	10/10/2011
90874	42	Weld, fabrication	9/28/2011	3156890	85.71668	1.01667	7	9/28/2011	10/5/2011
90874	42	Weld, fabrication	9/28/2011	3156890	0.60833	0	0	10/5/2011	10/5/2011
90874	42	Weld, fabrication	9/28/2011	3156890	10.6	0	0	10/4/2011	10/4/2011

90874	42	Weld, fabrication	9/28/2011	3156890	8.01111	0	0	10/6/2011	10/6/2011
90878	42	Weld, fabrication	9/29/2011	3173228	45.25	2.68333	3	10/4/2011	10/7/2011
90898	8	Weld, inlay	10/8/2011	3165624	15.65	0	28	9/10/2011	10/8/2011
90899	39	Operator error, missed dimension	10/8/2011	3170530	0.11667	4.61667	173	4/20/2011	10/10/2011
90899	39	Operator error, missed dimension	10/8/2011	3170530	0.7	0	0	10/10/2011	10/10/2011