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# APPLICATION OF LEAN SIX SIGMA FOR IMPROVING QUALITY LABORATORY PROCESS

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# APPLICATION OF LEAN SIX SIGMA FOR IMPROVING QUALITY LABORATORY PROCESS

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Oftentimes, manufacturing companies concentrate on improving the production processes and neglecting other processes like purchasing, IT, quality control, etc. Just like production processes, uncontrolled and non-optimized of any of these processes could be main reasons of product defects, late deliveries, and high costs. Recently, an automotive OEM (Original Equipment Manufacturer) in the southeastern United States faces difficulties in performing quality control operations in a way that matches the production pace. This inadequacy has increased due to changes in customer requirements and launches a new assembly line for a new customer. Therefore, the purpose of this study was to apply Lean Six Sigma methodology to reduce the turnaround time of the welding verification process by eliminating non-value-added activities. The researcher utilized DMAIC (Define, Measure, Analysis, Improve, and Control) approach to optimize the welding verification process. Through collecting the turnaround time and analyzing welding lab process, the researcher was able identify the redundant activities, then the researcher utilized the Visual Basic for Application (VBA) programming language for Microsoft Excel to streamline the reporting welds results step. The turnaround time of the weld verification process was reduced from 39.4 minutes to 30.4 minutes. Furthermore, the productivities of five welding lab technicians were increased by 16.4%, 20.1%, 27.55%, 40.86%, and 11.86%. Similarly, the sigma level was increased by about 1 sigma level, from 1.66 to 2.61. These results show that the process capability of the turnaround time indicates that the process

became more capable, however, it is still not capable of meeting the specified requirements. Therefore, more investigations need to be performed to improve the weld verification process to increase the process capability.

I dedicate this thesis to the memory of my first mentor, my beloved father. I also dedicate this work to my loving mother, my family and my friends who have supported me and inspired me to continue this journey.

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# Introduction

## Background

Product quality is a significant requirement in the automotive industry, especially when it is related to safety concerns. In 2016, the number of vehicles recalls in the United States was 927 recalls and covered 53.2 million vehicles (Malec, Smith, & Smuts, 2021). Automakers seek to avoid manufacturing issues by implementing rigorous quality control plans. Automakers also request their suppliers to provide parts and products that comply with their quality standards. Therefore, suppliers are required to implement adequate quality control procedures to handle this need. The quality inspection process is one of the methods used to ensure delivery of high-quality products. There are two types of inspections, off-line and on-line. Off-line inspection is the inspection performed after the completion of the machining process, whereas on-line inspection is done during the machining process. “Off-line inspection is a critical quality control step for many products when on-line inspection is either impossible or too costly to be implemented” (Chen, Pan, & Cui, 2017, p. 623).

The host company of this research is referred to company M throughout this study. Company M is a premier automotive parts supplier providing a range of body and chassis structures to the major automobile manufacturers in the United State of America. Company M is a leader in chassis, engine cradles and sub frames assemblies. The company performs metal forming processes including roll forming, casting, stamping, and bending. The company also utilizes the latest welding technologies in its assembly lines to meet its customers’ needs. Company M performs off-line inspections to examine welds conformity to the customers’ requirements. These inspections are performed after the welding process of the whole product is completed. This type of weld examination is called weld destructive testing. Weld destructive testing is a method used to determine the characteristics of the welds by taking a sample of a base material or welded structure (American Welding Society, n.d.). Company M utilizes a laboratory called Weld Lab to perform the weld destructive testing. The Weld Lab is a section of the quality department and performs weld testing to validate the welding processes performed throughout the assembly lines. The Weld Lab receives between 2,500 and 3,500 weld specimens daily. Each assembly line sends one part (sometimes more than one based on the production pace and number of changeovers) to the weld destruct section. The weld specimens are labeled and cut from frames by weld destruct technicians during the weld destruct process, and then the weld specimens are sent to the Weld Lab. In the Weld Lab, the lab technicians perform three main steps to examine the weld specimens. The first step is weld etching, which is a process of "coating or immersing a specimen with a solution that selectively eats away specific micro structural components, thus making others more evident and easy to study" (American Welding Society, n.d.). During this step, the weld specimens are placed in chemical solution called etching medium to reveal the structure of the base material and the weld. Then, for each weld specimen, a picture of the cross-section is taken using a microscope equipped with a camera connected to a computer. Then the welds' cross-section pictures are used to perform the metallographic examination. Metallographic examination is a "study of a material's microstructure. Metallographic examinations are generally performed by using optical microscopes to analyzing micrographs and provide insight into the past and future performance of base materials, parts, and experimental alloys" (American Welding Society, n.d.). The integrity and accuracy of welds are examined by measuring the weld characteristics such as the fusion depth of welding metal into the base materials. These characteristics are measured using specific software developed for this purpose. Once the measurement step is done, the weld examination results are sent to engineers and technicians in the production and quality departments to review the results and perform any corrective actions as needed. Lastly, a copy of the weld results is archived for the customers' audits.

Recently, the Weld Lab encountered a challenge when the weld verification process became a more time-consuming process due to the change in customers' requirements. In addition, the number of the performed weld examination has been increased due to launching a new assembly line for a new customer. This increment has added extra workload on the Weld Lab and must be managed using the available resources. This situation created pressure on the Weld Lab technicians to perform a larger number of time-consuming activities without sacrificing the accuracy of the weld examination process. Improper weld examination may lead to the delivery of defective products that might cause safety issues in addition to financial and bad reputation consequences. On the other hand, excessive and lengthy weld examination process has a negative impact on the on-time shipments deliveries. Late deliveries affect the customers' satisfaction negatively and cause significant financial penalties due to the failure to meet the customers' demands. One of the potential solutions for this situation is to increase the staff by recruiting more welding lab technicians. However, recruiting more employees means an increase in labor costs and operating costs such as equipment, computers, furniture, supplies, etc. Furthermore, this solution has no positive impact on the accuracy and the efficiency of the weld verification operations. Therefore, an effective weld examination process is essential to overcome this dilemma.

The main role of laboratories is to provide reliable, precise, and timely test results to support decision-making steps (Inal, et al., 2018). Similarly, Goswami, Singh, Chawla, Gupta, and Mallika (2010) identify "accuracy, precision, timeliness, and authenticity are the four pillars of efficient laboratory services" (p.376). Moreover, Laboratories are not isolated from challenges but, they have their own challenges. Sawalakhe, Desmukh, and Lakhe (2016) mentioned increase in workload, efficiency at lower costs, and maintaining quality standards and levels are the main challenges that testing laboratories face. To improve performance and cope with challenges, laboratories utilize process improvement methodologies. Lean and Six Sigma are two well-known methodologies that have been implemented successfully to various industries and processes including laboratories. The implementation of Lean and Six Sigma in laboratories varies based on purpose. Durur and Akbulut (2019) applied Lean to eliminate waste, whereas Six Sigam has been implemented to reduce errors and defects in laboratories (Vanker, van Wyk, Zemlin, & Erasmus, 2010; Elbireer, Le Chasseur, & Jackson, 2013; Levtzow & Willis, 2013). Other than reducing errors and defects in testing laboratories processes, many studies have discussed the implementation of Lean and Six Sigma to reduce the turnaround time of the testing processes. Researchers have applied Lean methodology and principles to reduce the turnaround time in testing laboratories (Cankovic, et al.., 2009; Letelier, et al.., 2021; Mitchell, Mandrekar, & Yao, 2014; Rutledge, Xu, & Simpson, 2010; Sugianto, et al.., 2015). On the other hand, Stoiljković, Milosavljević, Mladenović, Pavlović and Todorović (2014) implemented Six Sigma to reduce the turnaround time in a clinical testing laboratory. The integration of Lean and Six Sigma has been used to improve performance in various industries and settings. Regarding testing laboratories, Ibrahim, et al. (2022) implemented Lean Six Sigma to improve the sigma level in a clinical testing laboratory.

Although numerous studies discussed Lean and Six Sigma in various industries and settings, the implementation of Lean Six Sigma in testing laboratories has not fully covered. Most of the studies that address Lean and Six Sigma implementation in laboratories focus on applying them in clinical testing laboratories and very few studies cover the implementation of Lean and Six Sigma in engineering testing laboratories. Thus, this gap in the Lean Six Sigma literature needs to be explored and filled properly to understand Lean Six Sigma deployment in the engineering laboratories settings.

For two decades, Lean Six Sigma has been used successfully to eliminate waste, reduce the variations, and improve the process in manufacturing and services such as healthcare, education, information technology, banking, and finance. However, some aspects of Lean Six Sigma implementation are not intensively covered, such as, the implementation on Lean Six Sigma in the engineering testing laboratories. The aim of this research was to explore the implementation of Lean Six Sigma in an engineering laboratory and examine the efficiency of these methodologies to improve the Weld Lab process by reducing the turnaround time of the weld examination process. Reducing the turnaround time also optimizes the employee time, increases the staff productivity, and improves the entire process efficiency.

**Problem Statement**

Recently, company M faced a dilemma in performing quality control operations related to the weld verification process. This dilemma is generated by the following factors. The first factor is the change in a customer's requirement. The new requirement requires performing more welding measurements than the old requirements. Welding measurement is one of the most time-consuming activities in the welding examination process. Second, company M has built and launched a new assembly line for a new customer. This new assembly line has increased the number of welding examinations that need to be performed daily. These two factors have created pressure on Weld Lab to perform weld examination operations that should match the production pace. In addition, performing accurate weld examinations occasionally causes late shipment deliveries. Due to this situation, the Weld Lab is frequently behind the lab schedule. Furthermore, this situation might lead the lab technicians to perform fast but improper welding examinations to avoid late deliveries. To overcome this dilemma, a solution is required to speed up the weld verification process without sacrificing the examination accuracy.

**Significance of the Research**

Weld testing laboratory involves a set of processes that need to be completed to provide precise results in a timely manner. The weld testing results are essential and very important information that company M uses to deliver value to their customers. Weld testing results help company M to validate the welding processes throughout the assembly lines and ensure providing conforming products and free of weld defects. Reducing the turnaround time of the weld testing process would reduce the number of defective parts in the WIP, reduce the rework needed to correct non-conforming parts, and reduce scrap because early detection of weld defects would reduce the number of defective parts in the inventories. Reducing the turnaround time also reduces the operating costs, optimizes employees' time, and increases productivity. Furthermore, the lengthy weld testing process affects the production flow in the assembly line due to rework operations cannot be done in some of the late stages in the assembly process. Therefore, turnaround time reduction would enhance the production flow, improve on-time shipment deliveries, and increase customers' satisfaction by meeting customers' demands.

Despite the expansion of interest in implementation of Lean Six Sigma in various fields and settings, it is surprising that there is a deficiency in the literature regarding the implementation of Lean Six Sigma to reduce turnaround time in the engineering testing laboratories in general and in weld testing laboratories, in particular. This study will contribute to addressing this gap in the literature by examining the implementation of Lean Six Sigma in weld testing laboratory with a focus on turnaround time reduction. The study will also help organizations and continuous improvement participants to understand and evaluate the implementation of Lean Six Sigma in same or similar settings.

**Purpose of the Research**

The aim of this study was to address the Weld Lab problem using Lean Six Sigma (DMAIC) approach to define ways to optimize the Weld Lab process by reducing the turnaround time of the weld testing process. More specifically, the study aimed to identify and eliminate wastes and redundancy involved in the weld testing process to speed up the testing process and provide testing results in a timely manner. This study will aid company M in coping with the increase in the workload that is caused by changes in customers' requirements and launching a new assembly line.

**Hypotheses**

H1: Implementing Lean Six Sigma would lead to reducing the turnaround time of Weld Lab process.

H2: Implementing Lean Six Sigma would lead to increasing overall Weld Lab productivity by increasing the number of inspections performed by welding lab technicians.

### Assumptions

- The host company in this research study has not implemented any change on the welding lab process during the conduction of this study.
- The data of the lab technicians' productivity that were obtained from Weld Lab is accurate.
- Employees' performance will not be impacted by any factor that is beyond the scope of the study.

### Limitations

- The research is limited to M company (an automotive parts supplier at the southeastern of the United States of America).
- A variety set of Lean Six Sigma tools that can be used for every research study. Thus, the selection of a set of Lean Six Sigma tools might work differently for each company.

### Delimitations

- The research study is limited to improving weld verification process and will not include reducing weld defects.
- The aim of this research study is limited to reducing the turnaround time of the welding laboratory at M company.
- Due to the lack of time, the collected samples size is limited to 30 samples.

### Definitions of Terms

- 5 whys – "A simple principle of determining the root cause of a problem by asking "why" after each scenario to drive deeper and into more detail to get to the root cause of an issue" (Manos & Vincent, 2012, p. 387).

- Cause – effect analysis – “A type of tree diagram that is used to explore the multiple causes of a problem or potential causes of a risk (Westfall, 2016, p. 655).
- Cycle time – “The time required to complete one cycle of an operation” (Nanda & Robinson, 2011, p. 584).
- DMADV – “A data driven quality strategy for designing products and processes, it is an integral part of a Six Sigma quality initiative. It consists of five interconnected phases: define, measure, analyze, design, and verify” (Nanda & Robinson, 2011, p. 584).
- DMAIC – “A data driven quality strategy for improving processes and an integral part of a Six Sigma quality initiative. DMAIC is an acronym for define, measure, analyze, improve, and control” (Nanda & Robinson, 2011, p. 584).
- Excel’s macro – Is a set of Visual Basic for Application programming statements used to develop user-customized functions.
- Lead time – “The time required for one piece to move all the way through a system of processes, from start to finish” (Manos & Vincent, 2012, p. 390).
- Lean – “A systematic approach to identifying and eliminating waste (non-value-added activities) through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection” (Manos & Vincent, 2012, p. 390).
- Non-value-added (NVA) – “Activities or actions taken that add no real value to a product or service, making such activities or actions a form of waste (Nanda & Robinson, 2011, p. 588).
- Malcolm Baldrige National Quality Award – “An award established by the U.S. Congress in 1987 to raise awareness of quality management and to recognize U.S. companies that have implemented successful quality management systems (Summers, 2009, p. 547).

- SIPOC – "A process mapping method that examines each step in a process flow and characterizes it by its Inputs, Outputs, Customer (next step or end user), Supplier (source or predecessor), and the Process (the work performed or done at this step)" (Nanda & Robinson, 2011, p. 590).
- Six Sigma – "A methodology that provides businesses with the tool to improve the capability of their business processes. The increase in performance and the decrease in process variation led to defect reduction and improvement in profits, employee morale, and quality of product" (Summers, 2009, p. 551).
- Turnaround time (TAT) – "The total time elapsed between the start of a processing the inputs to the availability of the required output" (Nanda & Robinson, 2011, p. 73).
- User Acceptance Test (UAT) – Is a set of tests performed after developing or changing software to validate and verify that the software meets the user or client requirements.
- Value Stream Mapping (VSM) – "The process of creating a drawing of the value stream using icons that show the information flow and material flow of a process family (similar processing steps) in an organization (Manos & Vincent, 2012, p. 393).
- Visual Basic for Applications (VBA) – is a programming language developed for Microsoft Office programs.
- Waste – "Any activity that consumes resources but creates no value. Any activity that uses equipment, materials, parts space, employee time, or other corporate resources beyond the minimum amount required for value-added operations and for which the customer is unwilling to pay (Manos & Vincent, 2012, p. 393).
- Weld coupon (sample) – Two pieces of metal joined together by welding for performance qualification testing.

- Weld Lab – A facility that is supplied with special equipment to perform weld testing by analyzing and measuring welds specimen characteristics to examine the integrity and accuracy of welds.
- Work-in-process (WIP) – “The unfinished parts or products waiting in a manufacturing line for processing and completion” (Summers, 2009, p. 552).

# Chapter Two

## Literature Review

Globalization is one of the factors that lead companies to change the way to do their business. Globalization pushes companies to target not only the local or regional markets, but overseas markets as well. In addition, the rapid evolution of technology has increased the competition intensity in these markets. To overcome these challenges, companies seek to find ways to improve their performance to deliver high quality products or services at lower costs and within a shorter time. Lean and Six Sigma are the most popular methodologies to achieve these goals.

In many industries, the process performance relies importantly on time. While time might be a reason for losing money or customer dissatisfaction in some sectors, it is a life-threatening factor in other sectors such as in healthcare. This significant factor in any process is not out of the process improvement methodologies scope. Both Lean and Six Sigma deal with the time factor as an objective for process improvement endeavors. The Weld Lab in this case study frequently overloaded due to excessive and lengthy process. A time-consuming process in the Weld Lab means large WIP, higher defective parts, late deliveries, and less inspection accuracy. Applying process improvement methodologies to reduce the process time is crucial to avoid the above problems which in turn reduces the operation costs and increases customer satisfaction.

### Lean Approach

Lean is a process improvement methodology that focuses on eliminating waste through a systematic and continual improvement (Li, Laux, & Antony, 2019; Kam, et al., 2021). Thus, Lean methodology seeks improving the overall process efficiency by addressing and eliminating the non-value-added activities using a set of principles and best practices (Li, Laux, & Antony, 2019). The non-value-added activities are all the tasks and steps in the process that do not add value to the product or the service from the customer perspective. In other words, any activity that the customer is unwilling to pay for is considered a waste (Li, Laux, & Antony, 2019; Womack, Jones, & Roos, 2007). All types of waste can be classified in seven categories. These categories are overproduction, inventories, motion, transportation, defects, waiting, and over processing. Another type is now considered as a waste. The eighth waste is "intellect", and it is associated with unvalued or neglected ideas or skills (Gijo & Antony, 2019; Nanda & Robinson, 2011). Waste types might differ from process to another. Therefore, a clear definition of wastes is very important for successful waste elimination endeavor. Graban and Padgett (2008) define each type of waste in the laboratory environment (see Table 1).

Table 1

*Waste Types in Laboratories*

| Type of waste | Definition |
|---|---|
| Defects | Errors or problems that require inspection or rework. |
| Overproduction | Doing work earlier than necessary or more than is required by customers. |
| Transportation | Unnecessary distance traveled by patients or specimens. |
| Waiting | Idle time for specimens or employees. |
| Inventory | Excess or wasted inventory. |
| Motion | Unnecessary walking or exertion by employees. |
| Over Processing | Performing work that does not add value. |
| Talent | Not utilizing employee creativity and potential. |

Lean philosophy relays upon continual improvement, which means it is not a time limited process or being implemented for a certain period contrariwise, it is an ongoing process of improvement. To achieve the improvement objectives, Lean utilizes a set of tools and techniques that address at least one type of waste (Li, Laux, & Antony, 2019; Gijo & Antony, 2019). Thus, Lean aims to increase products and services value and increase customers' satisfactions through reducing time and efforts, lowering costs, minimizing inventories and defects, and superior adjustment to customers and markets demands.

The "Lean" term was coined in 1980's by researcher John Krafcik; but lean origins are traced back to the post-World War II era when Henry Ford and Alfred Sloan from General Motors developed a new concept that made the manufacturing moves from craft production to mass production. Ford's superiority spurred Eiji Toyoda and Taiichi Ohno from Toyota to devise the concept of lean production after several visits to Ford's assembly plant in Detroit. The craft production relays on utilizing skilled workers to build products based on customers' requirements, which means making one product at a time. The downside of this method is the high cost of production. Building luxury or customized cars is an example of craft production. On the other hand, mass production principle is about utilizing machines capabilities and the interchangeability of component and the simplicity to assemble them with limited consideration to product quality. In other words, mass production focuses on costs more than quality. Lean production, otherwise, utilizes multi-skilled workers and flexible machines to make a variety of high-quality products (Womack, Jones, & Roos, 2007).

After a profound consideration of Fords' assembly plant, Eiji Toyoda and Taiichi Ohno realized that copying Ford methodology is not suitable for Toyota, but there are many improvement opportunities that can be implemented. Thus, they developed a new production system called Toyota Production System or TPS which is the first lean production system (Womack, Jones, & Roos, 2007).

### Six Sigma Approach

The Six Sigma is a process improvement methodology. Pyzdek and Keller define Six Sigma as "a rigorous, focused, and highly effective implementation of proven quality principles and techniques. Incorporating elements from the work of many quality pioneers, Six Sigma aims for virtually error-free business performance" (2018, p.3). Six Sigma also is described as "a proven, data-driven suite for improvement methodologies based on a common philosophy and supported by measurement and tools for process and product improvement" (Nanda & Robinson, 2011). Sigma, σ, is a letter in Greek alphabet and statisticians have used sigma to assess the performance of any process, where the sigma level is used to describe the variation measurement in the process (Pyzdek & Keller, 2018). Thus, Six Sigma employs the data collected and measured using statistical and analytical techniques to identify and reduce defects and variation in the process. Whilst lean targets the waste in the process, Six Sigma focuses on identifying and eliminating the causes that make processes unstable and unpredictable which in turn cause variation in the process outputs. The strength of Six Sigma comes from its organized structure and the utilization of proven statistical tools to achieve disciplined process performance (Creed, et al., 2019; Kam, et al., 2021). Using a structured methodology, Six Sigma aims to drive processes to operate efficiently with almost error-free performance. This near perfection performance means the number of failures and errors that are generated by a process is less than four errors in every million opportunities, which is called defects per million opportunities or DPMO. To be precise, any process that operates in Six Sigma level does not generate more than 3.4 DPMO (Li, Laux, & Antony, 2019; Sanders & Karr, 2015; Stoiljković, Trajković, &

Stoiljković, 2011) (Figure 1) and (Table 2). Six Sigma uses two deployment models, DMAIC and DMADV. DMAIC model, Define – Measure – Analyze – Improve – Control, is used when the improvement project is applied to an existing process, product, or service. Whereas DMADV model, Define – Measure – Analyze – Design – Verify, is used when the Six Sigma goal is to develop a new or redesign a process, product, or a service (Pyzdek & Keller, 2018). Six Sigma has proven its capability as an improvement methodology and many organizations have gained benefits from Six Sigma in cost and time reduction and increasing quality and customer satisfaction.

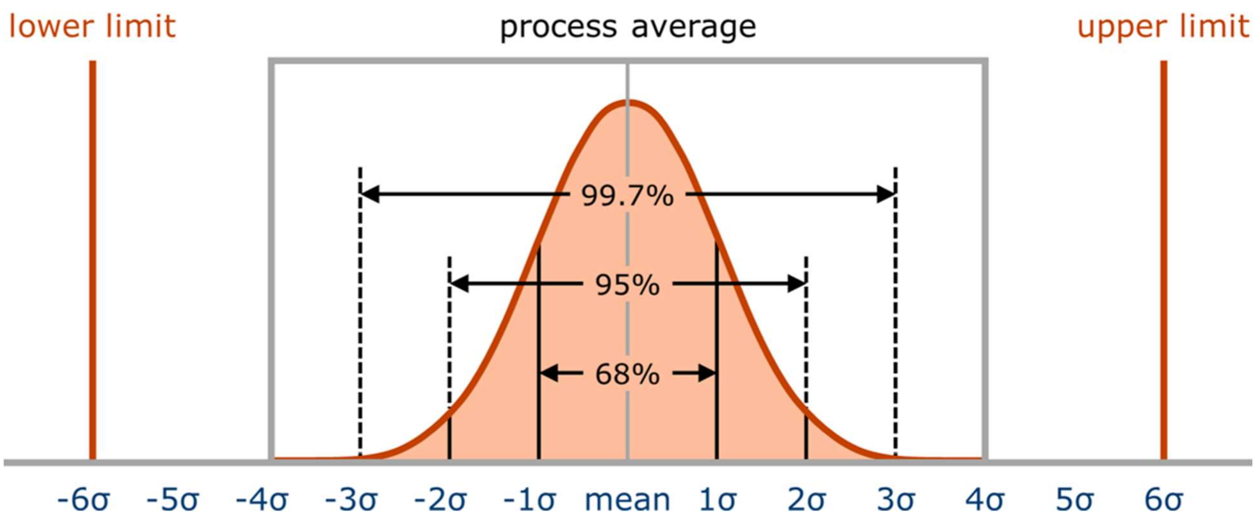



*Figure 1.* Normal distribution curve.

Table 2

*Sigma Level, DPMO, defect, and yield percentages*

| Sigma Level | DPMO | Defect% | Yield% |
|---|---|---|---|
| 6 | 3.4 | 0.00034 | 99.99966 |
| 5 | 233 | 0.023 | 99.977 |
| 4 | 6.210 | 0.62 | 99.38 |

| | | | |
|---|---|---|---|
| 3 | 66.807 | 6.68 | 93.33 |
| 2 | 308.537 | 30.8 | 69.2 |
| 1 | 691.462 | 69.1 | 30.9 |

Six Sigma was developed in the early 1980s by Motorola during the company pursuit to improve the quality of its products. To meet this objective, Bill Smith, who was an engineer at Motorola, studied the relationship between the product's life and the number of repairs that are done to the product during the manufacturing process. Smith's conclusion is, if a defective product was repaired during the manufacturing process, some other defects will be missed and then found by the customer. In contrast, if the product is defect free during the manufacturing process, it rarely fails during early use. Smith's study was the origin of Six Sigma (Nanda & Robinson, 2011).

In the beginning, Six Sigma was no more than a metric to measure how good Motorola was doing in terms of product quality. In a pursuit of Six Sigma, Motorola set 3.4 DPMO as an objective that is need to be achieved in order to handle the four sigma level of performance which was costing Motorola five to ten percent, 20 percent in some cases, of the company revenue to deal with products' defects and their impacts (Nanda & Robinson, 2011). During its pursuit to improve the quality of its products, Motorola won the Malcolm Baldrige National Quality Award in 1988 (Nanda & Robinson, 2011; Pyzdek & Keller, 2018). Then, using a systematic implementation of tools and techniques to detect and solve defects in the production processes and improving control actions to prevent defects occurrence, Motorola achieved Six Sigma level in 1993.

In the 1990s, the Six Sigma Research Institute was established by Motorola in cooperation with Honeywell, Texas instruments, Eastman Kodak, and other companies who are the early adopters of Six Sigma. General Electric has adopted Six Sigma after an estimation of the loss due the performing at 3.5 Sigma level by $ 7 billion. Then, by 2001, GE had achieved approximately $4.5 billion in cost saving. During the implementation of Six Sigma, GE revised the MAIC model, which was used by Motorola, to include “Define” phase to replace MAIC with DMAIC model. (Nanda & Robinson, 2011).

**Lean Six Sigma Synergy**

Lean and Six Sigma are the most popular improvement methodologies. Lean’s main goal is to eliminate waste in the process, whereas Six Sigma focuses on root causes of variation in the process. Both methodologies seek to improve processes and achieve to some extent similar goals. However, each method utilizes different techniques. Moreover, Six Sigma relay on data measurement, mathematical, techniques, and statistical analysis to make the improvement decisions, whereas Lean is a collection of techniques that have been proven effective (Nanda & Robinson, 2011). The combination of Lean and Six Sigma can achieve better outcomes than what either methodology can achieve independently (Bhat, Gijo, & Jnanesh, 2014).

Lean does not address variation within a process. Instead, it addresses the variation among processes. In Lean, this type of variation is described as a form of waste, which can be defined as waiting, rework, motion, and over processing (Gijo & Antony, 2019). In waiting, for instance, the processes do not perform at the same speed, that makes a process wait for the output of the previous processes and vice versa. Moreover, Lean does not aim to make a process perform under statistical control (Bhat, Antony, Gijo, & Cudney, 2019). Thus, one of the main limitations of Lean is its inability to solve issues related to process stability and capability. On the other hand, Six Sigma neither pursues to streamline the process nor address process flow and speed problems (Gijo & Antony, 2019). In other words, Six Sigma uses a scientific approach to create a more stable and predictable process with minimum variance in the process, which means Six Sigma focuses on the stability of the process but not the process speed (Sanders & Karr, 2015). However, Six Sigma can increase the process speed when it addresses the root causes of the variation of the process performance. This means Six Sigma is unable to speed up the process dramatically (George, 2003).

Another difference between Lean and Six Sigma is that Lean is a bottom-up approach where it stresses the importance of staff empowerment and their participation in improvement endeavors. In contrast, Six Sigma is a top-down approach where the improvement projects are mainly proposed and supervised by top management and performed by a group of skilled staff such as green and black belts (Gijo & Antony, 2019).Therefore, implementing an integrated approach that combines Lean and Six Sigma can increase the overall results. Implementing such combination helps maximizing and sustaining shareholders' value and increase customer satisfaction, improve quality, and reduce time and costs (George, 2003).

This combination creates a more robust and practical approach because both methodologies complement each other. The combination of the simplicity of the Lean tools and techniques with the rigor analysis of the Six Sigma assures long-term success supported by quantitative measurements to control and monitor results. (Nanda & Robinson, 2011). Bhat, et al. (2019) point out that the integration of Lean and Six Sigma tools optimizes resources utilization and optimizes accuracy and pace of the process at the same time. The implementation of Lean Six Sigma using DMAIC model is the most popular and effective approach for process improvement where Lean tools and techniques, and quantitative analysis of Six Sigma are applied at appropriate phases of DMAIC (Gijo & Antony, 2019).

**Lean Six Sigma beyond Production Area**

For decades, Lean and Six Sigma have proven their capability in the manufacturing sector. The benefits gained from successful implementation of Lean Six Sigma in manufacturing encouraged other sectors to adopt them as well. Education, information technology, finance, and healthcare are examples of the sectors that adopted Lean Six Sigma with the hope of gaining similar benefits that manufacturing companies have gained. Even though Lean was born in manufacturing environment; But the customer-centric thinking makes it applicable everywhere (Bhat, Gijo, & Jnanesh, 2014; Hines, Holweg, & Rich, 2004).

Likewise Lean, Nanda and Robinson (2011) point out three waves of Six Sigma adoption. When Six Sigma was invented in the 1980s by Motorola, it was viewed as an improvement methodology suitable only for manufacturing. In the 1990s, service sector organizations started adopting Six Sigma. Financial, healthcare, and insurance are examples of these sectors. In the 2000s, the Six Sigma adoption wave reached high-tech companies when some information technology, software and system engineering companies started adopting Six Sigma as part of their process improvement endeavors.

The common process improvement goals are improving quality, reducing costs, and reducing time. Achieving these goals reflects positively on customers as well as organizations through increasing customers' satisfaction and organizations' revenue. In the service sector, improving quality means the service should meet the customers' expectations. This means the service must be delivered on time and must be provided correctly every time. Assessing the service quality is not an easy mission due to quality in the service sector is something intangible. Voice of customer (VOC) should be taken into consideration to define the customer needs and requirements, which then can be turned into measurable data. Another characteristic that differentiates the service sector from the manufacturing sector is the processing time. Processes in service sector are usually slow (Bhat, Gijo, & Jnanesh, 2014; Stoiljković, Trajković, & Stoiljković, 2011). Slow processes have a significant impact on the service quality which in turn increases the costs and reduces the customers' satisfaction. Too much non-value-added activities and the unnecessary complexity are the main reasons of the process slowness in the services (Stoiljković, Trajković, & Stoiljković, 2011). Even though this study will be held in a manufacturing context, the study setting is more like the service sector due to the targeted process outputs are reports and data for internal and external customers. The purpose of this study is to reduce the turnaround time (TAT), eliminate redundancy and non-value-added activities and unnecessary complexity in the quality lab operations.

**Lean Six Sigma in Laboratories**

Like any process, laboratory process might have various types of waste, or variations that impact the performance efficiency. Implementing Lean in laboratories aims to perform testing more efficiently. Laboratories seek implementing lean to perform testing in minimum effort, using fewer resources in shorter time. Six Sigma, on the other hand, focuses on identifying the root causes of variance in the results and time. Thus, Lean Six Sigma analyzes laboratories performance to determine the inefficiencies and discover improvement opportunities to increase capacity and reduce time and costs (Stoiljković, Trajković, & Stoiljković, 2011). Testing laboratories are categorized into three main types: Clinical, Engineering and Environmental (Sawalakhe, Desmukh, & Lakhe, 2016). Quality laboratories are classified as engineering laboratories. Procedures for applying continuous improvement methodologies in laboratories vary significantly due to the difference in testing types and specimen number for each laboratory. However, the basic steps remain the same which comprise observing of the current workflow, identifying types of waste in materials and activities, change the process accordingly, monitor the new process and search for new continuous improvement opportunities (Dundas, et al., 2011).

Reviewing the literature shows that many studies have covered the implementation of Lean and Six Sigma for time reduction objective. However, there is a deficiency in the literature in terms of time reduction using Lean Six Sigma in engineering laboratories. Most of the studies that cover applying Lean Six Sigma for time reduction are about clinical laboratories. Even though this research will be hold in manufacturing environment, but the process that will be investigated, in many aspects, is very similar to processes in services environment, such as medical and clinical laboratories, due to the output of the Weld Lab process is a report and not a tangible product. In clinical labs, for instance, specimens are received and examined, and the results are sent to the physician. Likewise, the Weld Lab receives weld samples to be examined and then sends the results to quality and production departments.

The literature reviewed also shows that utilizing Lean and Six Sigma to improve the processes of clinical laboratories focuses on different improvement areas such as eliminating defects/errors, reducing time, utilizing resources. The literature review for this study will focus on the time reduction, process improvement, and resource utilization, staff time optimization due to these subjects comply with the scope of this project.

## Time Reduction Using Lean Six Sigma

Time reduction is one of the main objectives of Lean Six Sigma implementation. For decades, Lean and Six Sigma have been used to reduce various types of time in any process. Generally, there are three common types of time, cycle time, lead time and turnaround time. The cycle time "is the time required to complete one cycle of an operation" (Manos & Vincent, 2012, p. 389). The lead time is "the time a customer must wait to receive a product after placing an order" (Nanda & Robinson, 2011, p. 587). The lead time starts with request submission and ends with the delivery of the product or service. This means the lead time consists of the processing time, which contains set of cycle times, and the waiting time when the work is idle. Whereas the turnaround time is "the total time elapsed between the start of a processing the inputs to the availability of the required output" (Nanda & Robinson, 2011, p. 73). In other words, turnaround time does not include the time between creating the order and starting the process, and the time between the end of the process and the delivery. Each of Lean and Six Sigma addresses waste in time differently. While Lean addresses the waste time between processes (Gijo & Antony, 2019); Six Sigma focuses on reducing the cycle time (Nanda & Robinson, 2011).

### Turnaround Time Reduction

Improving the turnaround time is a crucial aspect in the laboratory quality management (Goswami, Singh, Chawla, Gupta, & Mallika, 2010). Laboratories pursue turnaround time reduction to improve the process efficiency, reduce costs and increase customer satisfaction. Lean and Six Sigma have been implemented in laboratories to improve processes performance by reducing the turnaround time. Lean's main goal is to identify and eliminate waste in the process. The literature review shows that the long turnaround in laboratories is generated by different causes. Staff traveling to obtain specimens or equipment was a most common reason of waste (Cankovic, et al.., 2009; Mitchell, Mandrekar, & Yao, 2014; Rutledge, Xu, & Simpson, 2010). Whilst, waiting and specimens' transportation were the second most common type of waste (Cankovic, et al.., 2009; Rutledge, Xu, & Simpson, 2010; Sugianto, et al.., 2015). On the other hand, Inal, et al. (2018) and Sanders and Karr (2015) point out that rework caused by errors or bad equipment were the main cause of the non-added activities which in turn increased the turnaround time of the testing process. In addition to the aforementioned types of waste, lack of standardization is another root cause of delay and turnaround time increment (Cankovic, et al.., 2009; Mitchell, Mandrekar, & Yao, 2014; Rutledge, Xu, & Simpson, 2010).

According to literature review, the broad aim of Lean and Six Sigma implementation in laboratories can be classified into two main categories. The first category is the errors and defects reduction. Durur and Akbulut (2019) presented a study to apply Lean methodology to achieve this goal, whereas Elbireer, Le Chasseur, & Jackson (2013), Levtzow & Willis (2013), and Vanker, van Wyk, Zemlin, & Erasmus (2010) applied Six Sigma for the same purpose. The other category of Lean and Six Sigma implementation in laboratories is the turnaround time reduction. Due to Lean methodology focuses on waste elimination, therefore, the turnaround time can be reduced via eliminating certain types of waste that are directly related to time, such as motion and transportation, or through eliminating other types of waste that non-directly related to time, such as extra processing, defects and errors that require re-performing some activities. Thus, Lean methodology reduces time through eliminating any activity that does not add value to the lab process and increases the processing time. On the other hand, turnaround time can be reduced through eliminating root causes of variations in the process and making the process more stable and under control.

### TAT Reduction Using Lean

Many researchers studied Lean implementation in laboratories with a focus on turnaround time reduction. Cankovic, et al. (2009) conducted a study to eliminate non-value-added activities in a clinical laboratory using Lean principles. The researchers identified the lack of standardization that causes delay in specimen delivery, waiting, and unnecessary specimen transportation and staff motion as the main non-value-added activities within the lab process. Applying Lean principles led to reduce the TAT average from 2.7 to 1.5 days which means 44% reduction. Similarly, Rutledge, Xu, and Simpson (2010) conducted a study to implement Lean principle (PDCA) in a clinical laboratory to eliminate waste in the laboratory process. The turnaround time was reduced from 54 to 23 min through implementation of 5S, work standardization, and redesigning the lab layout to reduce walking distance and reduce specimen travels distance. Mitchell, Mandrekar, and Yao (2014) achieved similar results using Lean methodology. They pointed out the weighted average turnaround time of eight test types was reduced by 47%. Testing specimens in a smaller batch size, reallocation of equipment to minimize motions, and applying the first-in, first-out rule for testing requests were the main improvement initiatives. Using Lean methodology and pursuing similar goals, Sugianto, et al. (2015) conducted a study to increase testing volume and improve overall process in a clinical laboratory. Using Kaizen and VSM the project eliminated non-value-added activities. The process efficiency improved by 63% and the total processing time reduced from 507 to 238 min. Likewise, Gupta, Kapil, & Sharma (2018) utilized Lean methodology to reduce turnaround time in clinical laboratories of a specialty hospital. 12 major non-value-added activities were identified in the blood testing laboratory and 5 major non-value-added activities in the biochemistry laboratory. The research study reduced the turnaround time from 180 to 95 minutes in the blood testing lab and from 268 to 208 min in the biochemistry lab.

Based on the aforementioned studies, the turnaround time reduction percentages were between 40% and 55% percent in general. However, Letelier, et al. (2021) achieved mediocre results compared to previous studies. Their implementation of Lean in a clinical laboratory shows that the TAT reduced from 84 to 73 min which means 13% reduction for one type of test. The reduction in time of the other two types of tests was not significant (1.2% and 0.3%) and in some cases the turnaround time increased.

**TAT Reduction Using Lean Six Sigma**

The combination of Lean and Six Sigma create a simple but robust collection of tools and technique that are applicable for any problem and in any environment (Nanda & Robinson, 2011). Bhat, Antony, Gijo, & Cudney (2019) state that "the integration of Lean and Six Sigma can accomplish better results than what either system can independently achieve" (p. 93). The following part presents studies that implemented Lean Six Sigma to reduce turnaround time in laboratories environment. Sanders et al. (2015) carried out a case study to improve the blood draw and specimen process for emergency department using Lean Six Sigma methodology. The main goal was to reduce the turnaround time (TAT) of specimen process; however, the project significantly improved several other processes. The reduction percentage, in various processes, ranges between 2% to 50%. The most significant time reduction was achieved on a blood test. The median TAT was reduced form 15-11 minutes, and the reduction percentage is 30%; and the TAT variation reduced additional processing time from 45-60 minutes to 23-30 minutes, and the reduction percentage is 50%. In addition to the reduction in processing time, the project also achieved a 50% reduction of vial usage, 50% of unused or extra specimens, and 90% reduction of ED specimens without orders. Even though the project team did not abide to implement Six Sigma strictly, the project resulted in several significant improvements. Similarly, Inal et al. (2018) carried out a case study to simplify the workflow of a clinical laboratory. The study used Lean Six Sigma DMAIC to reduce the turnaround time and eliminate the non-value-added activities. Sorting plastic bags, sorting request forms, and relabeling the samples with the barcode were the non-value activities that were identified through the workflow analysis. Retraining staff and replacing the writing order form with an electronic one has improved the process and reduced the turnaround time. Lean Six Sigma implementation results show that 3 hours and 22 min of non-value-added activities were eliminated. Thus, the TAT was reduced from 68 to 59 min.

Outside of clinical laboratories, Alfaro et al. (2020) carried out a case study to improve the process of the department of forensic sciences ballistics unit. The project goal was to reduce the turnaround time of examination done on evidence by the unit. The project team utilized the Lean Six Sigma DMAIC approach to improve the process and reduce the turnaround time. The project team identified the most three processes that contain non-value-added activities and constraints. These three processes are: describing evidence, comparison, and reporting. After finishing the five Six Sigma phases, the turnaround time was reduced from 4.6 months to 1 month, the total amount of pending cases was reduced from 259 to 62 cases, and the lead time went from 2620 to 1060 min. Financially, the project saving was $27,575 per year.

Even though the aforementioned studies utilized Lean Six Sigma approach, the implementation focused on applying Lean tools within the Six Sigma’s DMAIC approach. Therefore, the above studies do not cover the calculation of defects and sigma level before and after the implementation of Lean Six Sigma. In contrast, Ibrahim, et al. (2022) conducted a study to apply Lean Six Sigma in a clinical laboratory. In this study, the researchers focused on calculating the defects and sigma level before and after the implementation of Lean Six Sigma. The non-conforming tests were defined as the reports that are verified after a target time. Therefore, any late test result was counted as a defect or non-conforming result. Using this approach, the researchers were able to count the defects and then calculate the sigma level. During the measure phase, the percentage of late results was 19% and the sigma level was 2.4. The late results were reduced to 1% and the sigma level improved to 3.7 after the implementation of Lean Six Sigma.

Reducing turnaround time using Lean Six Sigma is not limited to laboratories environment. Several studies have covered this topic. The next part gives a brief about studies that discuss Lean Six Sigma implementation to reduce the turnaround time within healthcare environment. Davies et al. (2019) presented a case study to implement Lean Six Sigma to optimize the nurses' time and reduce the patient turnaround time PTT. The results show that an average of 15 min of patient time was reduced. The admission time was reduced to 5 min which means 10 min time savings on nursing time. Similarly, Schoonhoven et al. (2011) conducted a case study to improve the quality of the care provided by the hospital and improve the resources allocation. The study focuses on two objectives. The first objective aims to shorten the admission time for new patients and throughput time for consultation. The post-project results show that the admission time was reduced from 2 weeks to less than 10 days for 95% of new patients, whereas the throughput time was reduced from 5 weeks to 14 days. Another study presented by White et al. (2017) to reduce the radiology turnaround time and patient waiting time. The researchers applied system engineering using lean methodologies to reduce the radiology transport delays.

After a year of reorganizing the process, the transport time was reduced 24%, and 5,712 hours reduction of the patient waiting time per year. Lastly, Bhat et al. (2019) conducted a multiple case study analysis to investigate the implementation of Lean Six Sigma in healthcare facilities. As a result of the first case study, the sigma level improved from 0.38 to 3.1, 65% reduction in waiting time, and 79% reduction in standard deviation. In the second case study, the TAT reduced from 52 to 39 min. whereas in the third case study, the TAT was reduced 50%.

Despite the abundance in the research studies that cover the implementation of Lean Six Sigma to reduce the turnaround time, there is a lack of literature that covers the engineering laboratories setting in general and weld testing laboratory in particular.

# Chapter Three

## Methodology

The aim of this study was to address the Weld Lab problem using Lean Six Sigma (DMAIC) approach and define ways to optimize the weld testing process by reducing the turnaround time, eliminating redundancy, and increasing overall productivity. This chapter describes research methodology that was used to test the research hypotheses. The researcher utilized quantitative research methodology in this study, and the research design was the pretest-posttest design. This design is implemented by performing pretest measure and followed by an intervention then measuring the posttest for a single group (Creswell & Creswell, 2018). The selected methodology and design were implemented through collecting the current performance data using statistical tools, and then implement Lean Six Sigma DMAIC, then collect post intervention performance data, and lastly interpret the new performance data to confirm or refute the research hypotheses. The research hypotheses presented in this study were:

H1: Implementing Lean Six Sigma would lead to reducing the turnaround time of Weld Lab process.

H2: Implementing Lean Six Sigma would lead to increasing overall Weld Lab productivity by increasing the number of inspections performed by welding lab technicians.

The researcher employed the Lean Six Sigma DMAIC approach as a treatment to confirm or refute the hypothesis above.

**Welding Lab Process**

The Weld Lab in company M is part of the quality department and is responsible for performing weld testing to verify the welding operations that are done throughout the assembly lines. Weld samples are labeled and cut during welds destructive operations. Weld destructive technicians cut a piece of weld and base materials of each weld section in chassis or engine cradles to be tested in the Weld Lab. Then the side of weld samples is ground and polished by weld destructive technicians before they are sent to Weld Lab in designated boxes (see Figure 2). When the box of weld samples arrives at the Weld Lab, they are placed on designated shelves with a classification based on program / product.

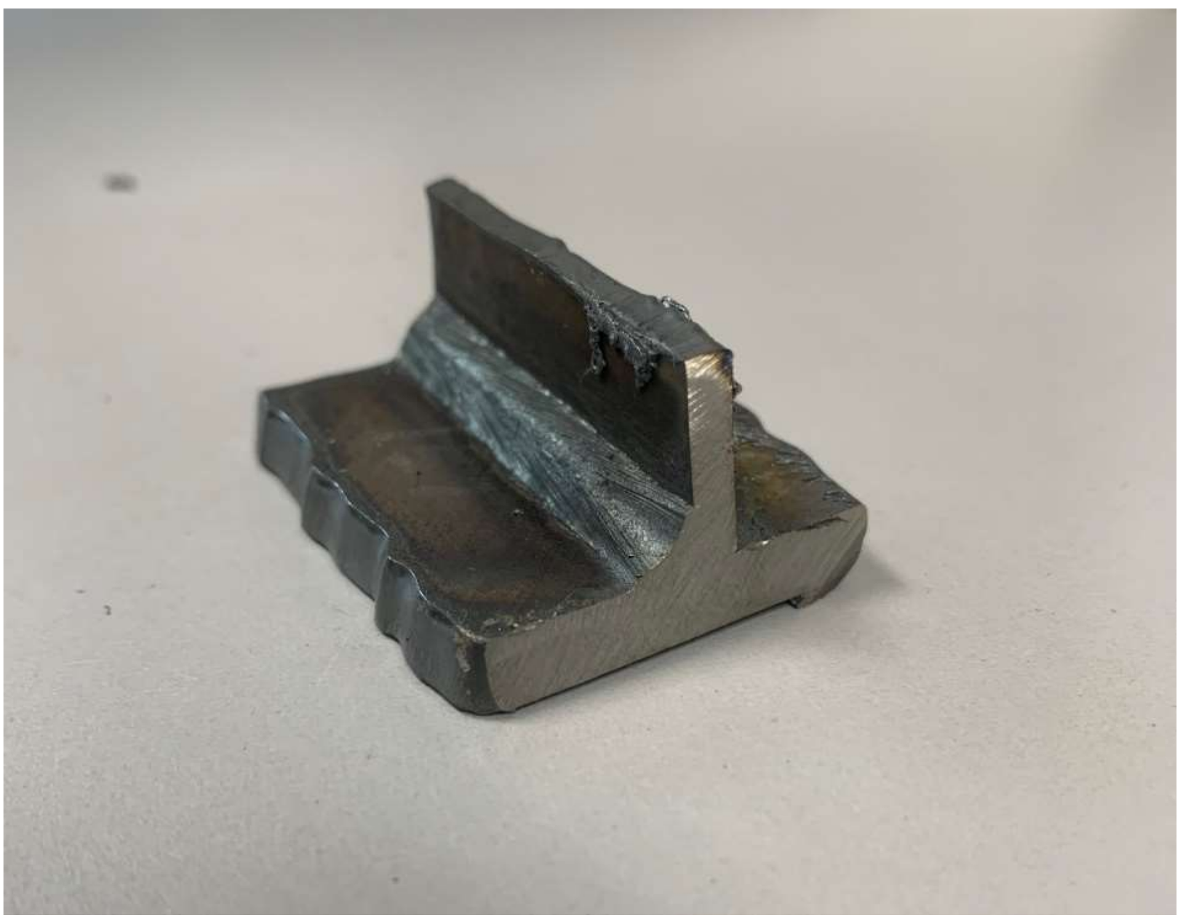
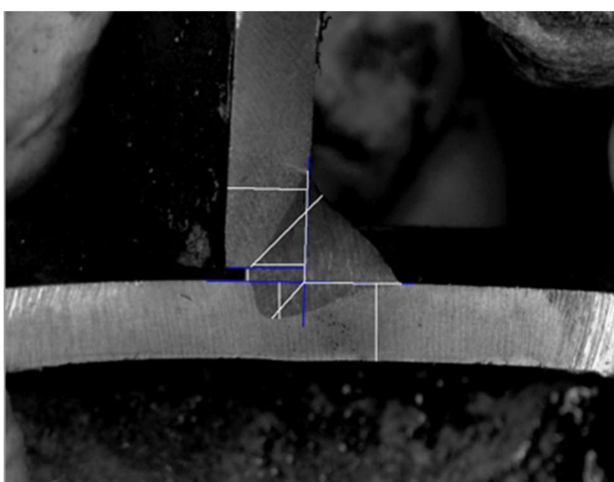


*Figure2*. A welding sample.

The Weld Lab uses a FIFO (first-in, first-out) approach to set the work order. However, some products have higher priority, so they are processed once they arrive at the lab. Therefore, once a welding lab technician is ready to perform a new welding examination, the Lab technician obtains the box of the weld samples with the higher priority to be examined. The examination process starts with recording the product's information to which the weld samples belong. This information includes the serial no, date, customer, and product type; and then this information must be entered into software that is used for capturing the weld cross-section pictures, measuring weld, and generating the final report. The next step is dipping the weld samples in a chemical solution (etching solution) that makes the weld to be distinguished from the base materials. Then the weld samples are placed under a microscope equipped with a camera to capture the cross-section picture of the weld (see Figure 3). Welding Lab technicians repeat this step to all welding samples. Once all weld samples are pictured, the technician start measuring the cross-section pictures of the welds to examine the weld characteristics (see Figure 4), and then the weld testing report is generated and sent to the engineers and technician in the assembly and quality departments. The last step is recording the weld testing results in an Excel sheet used to track and archive the results.

*Figure 3*. Weld cross-section picture.



| Characteristic | (mm) | % | Status |
|---|---|---|---|
| Root Penetration | 2.50 | 64.5% | Pass |
| 10% of T1 minimum / 30% of T1 goal | | | |
| Leg 1 Penetration | 2.69 | 69.3% | Pass |
| 10% of T1 minimum / 30% of T2 goal | | | |
| Leg 2 Penetration | 1.86 | 48.0% | Pass |
| 10% of T1 minimum / 30% of T2 goal | | | |
| Actual Throat | 5.25 | 135.4% | Pass |
| 70% of T1 minimum | | | |
| Leg Length Fusion 1 | 5.62 | 128.6% | Pass |
| T1<1.5 must=T1+ gap | | T1>=1.5 must=70% of T1+gap | |
| Leg Length Fusion 2 | 5.16 | 133.0% | Pass |
| T1<1.5 must=T1+ gap | | T1>=1.5 must=70% of T1+gap | |
| Undercut | 0 | | Pass |
| 20% of T1 Maximum (center) | | | |
| Gap | 0.63 | 16.3% | Pass |
| T1<1.5 must be <50% of T1 or<1 | | T1>=1.5 must be <70% of T1 or<1.5 | |

*Leg length fusion does not include overlap

*Leg length & gap measured separate

*Figure 4*. Weld measurement from a weld testing report.

## DMAIC Approach

The approach that the researcher used in this study is the combination of Lean and Six Sigma DMAIC approach. This combination of Lean and Six Sigma allows the researcher to use tools from both Lean and Six Sigma to benefit from the strengths of each methodology and achieve better results. The DMAIC approach includes five phases: Define, Measure, Analysis, Improve, and Control.

### Define phase

Six Sigma projects success significantly relay on the Define phase. The Define phase establishes the foundations of the entire project. The aim of this phase was to define the problem, form the project team, define project scope, objectives, and develop project charter. The problem statement was the basis for the next activities in the Define phase. Incorrect problem statements can direct the project toward directions away from the project purpose. In this phase, the problem statement in the weld verification process was described in detail. The problem statement states that the Welding Lab is struggling to handle excessive workload to provide precise welding verification results in a timely manner. Also, the problem statement mentioned that the current capability of the Weld Lab area is limited, where there are untapped opportunities to improve performance. After defining the problem, the project team was established. The team consists of members who have the knowledge and skills needed according to the purpose of the project. The roles and responsibilities of each team member were determined. The next step was defining the project scope. In this step the domain of the project was specified and what areas to be investigated and analyzed. The project objectives describe the desired outcome that the project team wants to achieve. The objective of this project was to reduce the turnaround time by identifying and eliminating waste and redundancy involved in the weld verification process. The last step in the Define phase was developing the project charter which contains more details such as defining the product, process, and the metrics were used to measure the process performance.

**Measure phase**

The aim of this phase was to measure the current process. In this phase, the process was measured using metrics that were defined in the previous phase to establish the baseline performance of the current process. Value Stream Mapping VSM was used to measure the welding verification process. Using VSM, the non-value-added and value-added activities were determined and measured in the weld verification process.

***Turnaround time baseline***. The turnaround time is the total time elapsed between the start of processing the welding coupons to the availability of the welding verification results. The turnaround time data was collected by observing the process and recording the time of each step in the welding verification process.

***Lab technician productivity.*** This metric is the number of welding coupons archived and measured by each welding lab technician. The data of each lab technician's productivity is collected by the welding lab leader and saved in Microsoft Excel sheet on daily basis. The purpose of this metric was to validate the reduction of the turnaround time. Reducing the turnaround time should reflect on the lab technicians' productivity by releasing some time from the processing time and assigning this time to perform more weld verifications tasks.

***Sigma level baseline.*** Since this project is a Lean Six Sigma project, the sigma level was calculated to evaluate the improvement achieved by this project. This metric was also used to validate the reduction of the turnaround time. Ibrahim, et al. (2022) presented a method to calculate the DPMO by selecting a specific time to be the due time, so defects or nonconforming reports are verified after that time. Likewise, the project team selected a time frame for the weld verification process. This time frame represents the amount of time required to complete the welding verification inspection, and the inspection report must be sent within that time. Thus, defects or nonconforming reports are those exceeded that time. Any increase in the Sigma level means the weld verification process is improved thus, the number of weld verification tasks which exceed the time frame limits is reduced.

**Analysis phase**

The goal of this phase was to study the process and identify methods to eliminate the deficiency in the current process performance to achieve the desired performance. The Welding Lab process was analyzed to eliminate redundancy and non-value-added activities. Eliminating waste and redundancy improves the process efficiency and reduces the turnaround time. The VSM was analyzed to determine the redundancy and the non-value-added activities of the welding lab process. One of the main steps in the welding verification process is reporting the welding verification results. This step consists of documentation activities. Therefore, the researcher proposed using Document Value Mapping (DVM) to analyze this step in more detail. The DVM provides analysis of each section of the document that is being analyzed (Nanda & Robinson, 2011). The DVM helped the project team to identify the non-value-added activities and the redundancy in all documentation activities involved in the welding verification process. The next step in the Analysis phase was analyzing the data of the turnaround time and the data of the welding lab technicians' productivity. The researcher utilized the Minitab software to perform the statistical and graphical analyses of the collected data. Normality tests were performed to verify that the collected data comes from a normally distributed population. Then, Individual and Moving Ranges graphs were developed to verify that the current process is stable and under control. The last step in the statistical and graphical analysis was the Process Capability analysis. The process capabilities were used to evaluate the current process and to determine whether the current process performance can meet the customers' requirements or not.

**Improve phase**

The aim of this phase was to propose solutions to address the problem that was being investigated. Then, the proposed solutions must be evaluated to determine the outcomes and the benefits of these solutions. Once solutions were evaluated and approved, the next step was the solutions implementation. The last step in the Improve phase was validating the outcomes of the new process. According to the outcomes of the Analysis phase, the project team discussed several solutions to improve the weld verification process. Two solutions were excluded from this project. These solutions require more resources that were not available for this project. Thus, these solutions will be discussed and implemented later as separate projects. One solution was proposed and implemented to reduce the turnaround time by eliminating redundancy and non-value-added activities from the process. The solution was utilizing the Visual Basic for Application (VBA) to streamline the activities of reporting the weld verification results. Several Microsoft Excel macros were developed by the researcher to perform the reporting activities in automatic way. The macros solution was validated in two ways. First, by performing User Acceptance Test (UAT) to validate the benefits of the Excel macros. Second, by collecting new data of metric used in this project, turnaround time and the productivity of the welding lab technicians.

**Control phase**

The aim of this phase was to sustain the improvements and ensure that the new process will not deviate from the target. The improvements were maintained using control tools to standardize and document the new process. Moreover, a control plan was defined and implemented to track the process performance. The aim of the control plan was to monitor the process and identify any deviation in the process performance. The control plan was implemented on a regular basis to ensure that the process is performing within the desired limits. Sawalakhe, Desmukh, & Lakhe (2016) presented a model to monitor and evaluate laboratory performance (Figure 5).

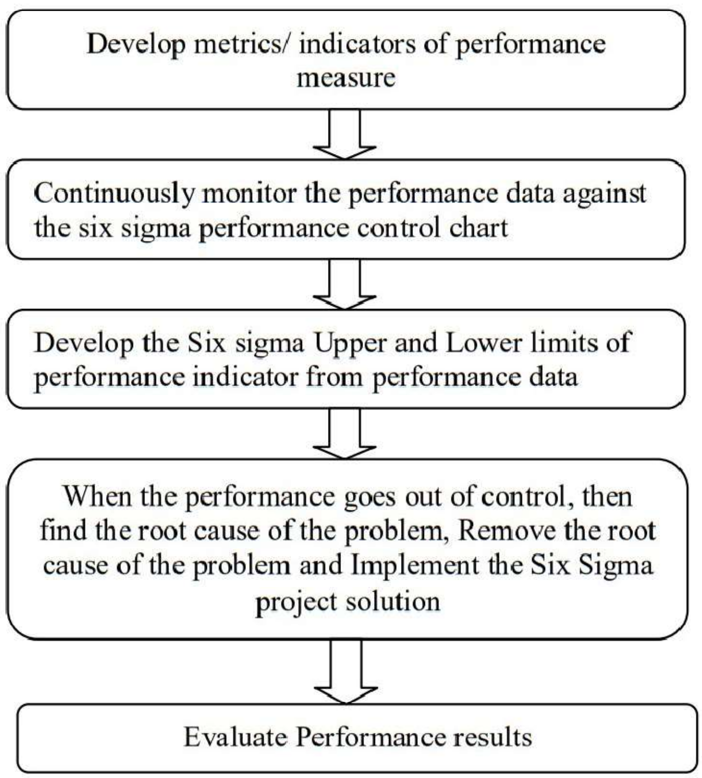



*Figure 5.* A model to monitor and evaluate the laboratory performance (Sawalakhe, Desmukh, & Lakhe, 2016).

The model suggests developing performance indicators and identifying the performance lower and upper limits. These indicators and performance limits are utilized to compare the process performance against the control chart. Then root causes should be investigated whenever the performance goes beyond limits. Proper solutions must be evaluated and implemented to bring the process back under control again. Eventually, results are evaluated and documented.

To sustain the improvements in the welding verification process, two performance indicators were utilized. The first indicator was the turnaround time, and the second indicator was the lab technicians' productivity. Both indictors were recorded and compared against the control chart monthly to monitor the welding lab performance.

**Data Collection and Analysis**

The turnaround data of the pretest and posttest were collected by observing the weld verification process and then the collected samples were inserted into Excel spreadsheet, whilst the welding lab technicians' productivity of the pretest and posttest were collected into Excel spreadsheet by the Weld Lab leader and then the samples were given to the researcher. The researcher utilized Minitab software to analyze the collected data of the pretest and posttest. The researcher used Minitab software to create the control charts and the process capability charts for the turnaround time data, and the researcher used Microsoft Excel software to calculate the DPMO and the sigma level.

# Chapter Four

## Results and Discussion

This chapter provides details of the implementation of the DMAIC approach used throughout this project.

### Define phase

**Developing project charter**. To establish the foundation of the Lean Six Sigma project, the project team developed the project charter shown in Appendix A. The project charter defines the research problem, the process to be improved, objectives and metrics, and the project team members. The project charter also defined the business benefits, the project schedule, key milestones, and date of completion of each step as well as the project completion date. See appendix A.

**Forming the project team**. The next step in this phase was the project team formation. The team consisted of two welding lab technicians, welding lab leader, Green Belt and Black Belt holders, project leader, and project champion.

**Define the research problem.** Weld Lab at M company is overloaded with excessive and lengthy weld verification process which makes Weld Lab is frequently behind the lab schedule. This situation was caused by two factors. First, one of M company's customers changed the requirements of the weld verification test by requesting that all welds be measured. Before this change, the welding lab technicians measure only the weld that classified as a concern during the archive step (capturing the weld cross-section pictures). All the welds that are visually classified as conforming welds, are not measured. Therefore, welding lab technicians must perform more welding measurements which consumes more time. The second factor is company M launched a new assembly line for a new customer. This new assembly line has increased the number of weld verification tests that need to be performed daily.

**Define the project scope**. The weld verification process consists of two main steps. The first step is the weld destruction. During this step the welds that need to be tested are labeled with the weld identification number (ID). Then labeled welds are cut, and then the cross section of the weld is ground, polished using sand disk and then sent to the Weld Lab. These steps prepare the welding samples (weld coupons) for the next steps which are held in the welding lab. Also, all these steps are done in the weld destruction section. The above steps are not included in this project; thus, the scope of the project is the welding lab only.

**Define the project objectives**. The aim of this project was to define ways to optimize the weld verification process by reducing the turnaround time of the weld testing process. The objective of this project was to identify and eliminate waste and redundancy involved in the weld testing process to speed up the testing process and provide testing results in a timely manner.

**Define the product.** M company assembles eighteen products classified into six programs. The project team chose one program (referred to as P1 throughout this study). This program has the biggest number of products with six products and the number of welds in this program is over a thousand welds. Then the team chose one product from program P1. The selected product is referred to as H in this study. Company M assembles product H over three working shifts. The welding lab receives three samples of product H daily. One sample on each shift, which means one sample every eight hours. However, the actual number of product H that is sent to the welding lab for welding inspection depends on the production schedule and the customer demand. Thus, sometimes the welding lab receives less than three parts daily, and sometimes the welding lab does not receive any part if the assembly line of product H is shutdown.

Product H has 59 welds, and the number of weld samples (coupons) varies between 34 to 59. The inspection that has the biggest number of weld coupons, which is 59, is the weld verification that inspects all welds in product H (called "FC" which stands for full cut), whereas 34 weld coupons represent the inspection of the customer critical welds only. A full cut inspection is performed once a week. However, the weld inspection that tests the minimum of weld coupons, which is 34, is the inspection that verifies the customer critical welds only. The customer critical (CC) welds must be inspected daily. The welding lab performs another type of inspection called (CCN). The letter "N" stands for "needs". This type of inspection consists of customer critical welds (CC) and any weld that was out of specification in the last inspection. Therefore, the CCN is the type of inspection when the number of weld coupons is between 34 and 59 welds.

To minimize the variation in the number of weld coupons, the project team decided that the samples that are been collected are only the inspections which have the number of weld coupons is between 34 and 40 coupons only. This decision allowed the team to collect more data since most of the weld inspections performed on product H contain weld coupons between 34 and 40.

**Define the process.** The aim of this step was to describe the process in detail. The project team utilized SIPOC (Figure 6), and Process Map (Figure 7) to describe the process. The project team held a meeting to create a SIPOC diagram to define the suppliers and the internal and external customers; and specify the process's inputs and outputs. To give more details about the weld verification process, a Process Map was made based on the information given by the Weld Lab's area leader and the welding lab technicians. The Weld verification Process Map facilitated the understanding of the process activities, and it described the process in detail. The details provided by the Process Map were very useful in the measure and analysis phases.

| Supplier | Input | Process | Output | Customer |
|---|---|---|---|---|
| • Assembly lines<br>• Weld destruct. | • Weld samples (Coupons).<br>• JSN (Job Serial No.)<br>• Work order.<br>• Cut sheet.<br>• Tag. | Grab weld coupons & record info.<br>↓<br>Etch weld coupons.<br>↓<br>Archive weld images.<br>↓<br>Measure the weld coupons.<br>↓<br>Generate Weld reports (Results)<br>↓<br>Email the weld reports.<br>↓<br>Update weld trend tracker. | • Weld report.<br>• Cover sheet.<br>• Weld alert.<br>• Email.<br>• Radio call. | <u>Internal customers</u><br>• Welding technicians.<br>• Welding engineers.<br>• Area/Team Leader.<br>• Quality Technicians.<br>• Quality Engineers.<br><br><u>External customers</u><br>• Automakers. |

*Figure 6.* Weld verification SIPOC diagram.

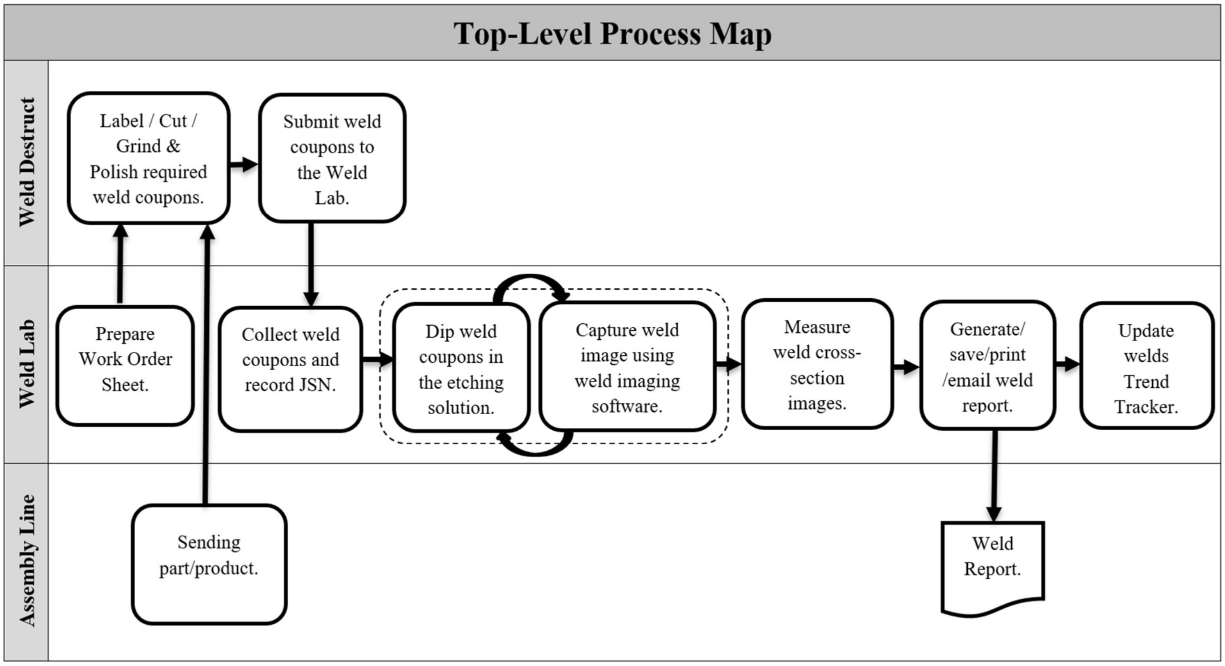



*Figure 7.* Weld verification Process Map diagram.

**Define process metrics.** The objective of this step was to define valid and reliable metrics based on the process description and the project objectives. The metrics were used to test the hypotheses in this study. The researcher suggested a set of metrics that are suitable for the study hypotheses.

1. Metric 1: Turnaround time (TAT)

   The project team decided to use turnaround time (TAT) as a primary metric. This metric is the time elapsed between the start of processing the weld coupons to the availability of the weld testing report. Therefore, the time starts when a welding lab technician starts recording the product information in the welding lab software and ends when the welding lab technician generates and sends the final weld testing report. The turnaround time was measured before and after the implementation of the research treatment which is the implementation of Lean Six Sigma. This metric was used to test hypothesis 1 (H1: Implementing Lean Six Sigma would lead to reducing the turnaround time of Weld Lab process). The turnaround time was calculated in minutes.

2. Metric 2: Lab technicians' productivity

   This metric measures the Weld Lab productivity. The metric describes the total number of welds that are tested by each lab technician during a single working shift (8 hours). This metric aids the researcher to test hypothesis 2 (H2: Implementing Lean Six Sigma would lead to increasing overall Weld Lab productivity by increasing the number of inspections performed by welding lab technicians). This metric was also measured before and after the project.

3. Metric 3: Sigma Level

   The goal of this study was to reduce the turnaround time of the weld testing process, not the defective welds or testing errors. Using this approach, the project team were able to calculate the DPMO and then the sigma level of the lab process performance. The two metrics in this phase and the sigma level were used to evaluate the improvements achieved using Lean Six Sigma implementation.

After the project charter had been approved by the top management, appropriate training was given to the project team. The training covered Lean Six Sigma main idea and a set of Lean Six Sigma tools and technique and how they are used. Tools such as SIPOC and Process Map were used to describe the Weld Lab process clearly and properly identify the improvement opportunities in the process.

**Measure phase**

**Measure process baselines**. The aim of this step was to measure the performance of the current process using the metrics defined in the previous phase. The project team utilized value stream mapping (VSM) to visualize the process and measure the value-added and non-value-added activities (Figure 8).

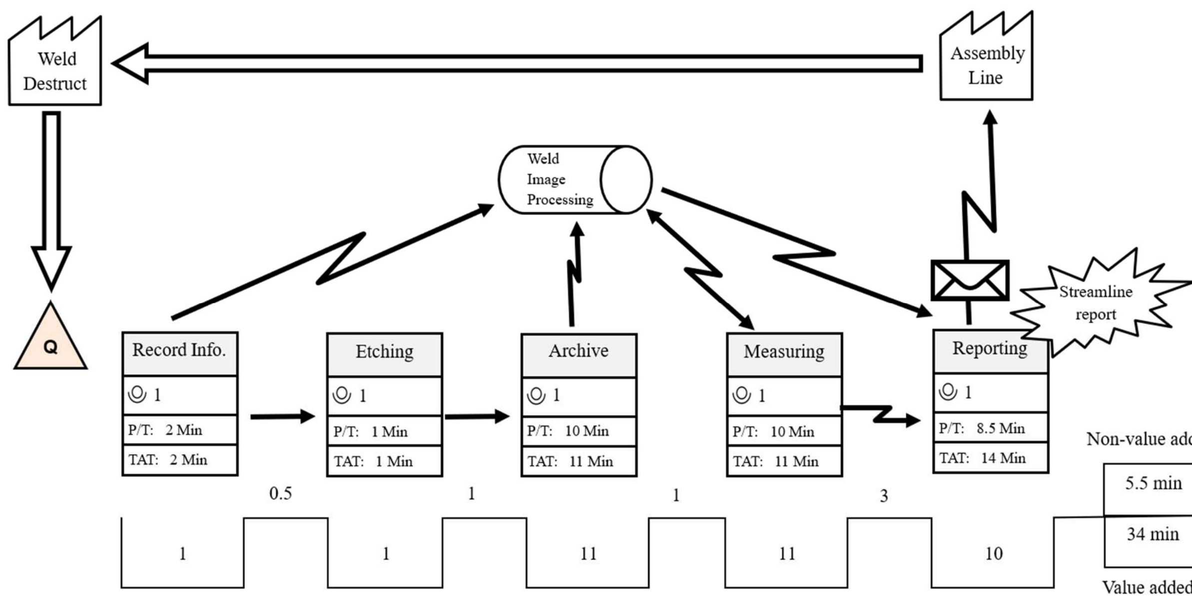



*Figure 8.* Current state of weld verification value stream mapping.

***Turnaround time baseline.*** The turnaround time starts when the lab technician enters the serial number of the sample in the weld image processing software, and it ends when the last step in the process is finished. Table 3 shows the turnaround time data collected during the measure phase.

Table 3

*Turnaround time for the product H before the project.*

| Sample # | Date | Lab Technician | Turnaround Time (Min) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 1 | 10/27/2022 | Technician 1 | 38 |
| 2 | 11/1/2022 | Technician 2 | 41 |
| 3 | 11/2/2022 | Technician 1 | 36 |
| 4 | 11/4/2022 | Technician 3 | 35 |
| 5 | 11/9/2022 | Technician 2 | 49 |
| 6 | 11/10/2022 | Technician 4 | 39 |
| 7 | 11/15/2022 | Technician 5 | 42 |
| 8 | 11/17/2022 | Technician 5 | 33 |
| 9 | 11/18/2022 | Technician 3 | 51 |
| 10 | 11/22/2022 | Technician 1 | 43 |
| 11 | 11/29/2022 | Technician 4 | 45 |
| 12 | 11/30/2022 | Technician 1 | 24 |
| 13 | 12/2/2022 | Technician 5 | 46 |
| 14 | 12/6/2022 | Technician 2 | 40 |
| 15 | 12/7/2022 | Technician 4 | 51 |
| 16 | 12/9/2022 | Technician 1 | 50 |
| 17 | 12/13/2022 | Technician 3 | 36 |
| 18 | 12/16/2022 | Technician 5 | 29 |
| 19 | 12/20/2022 | Technician 1 | 42 |
| 20 | 12/21/2022 | Technician 3 | 43 |
| 21 | 1/4/2023 | Technician 4 | 33 |
| 22 | 1/6/2023 | Technician 3 | 38 |
| 23 | 1/10/2023 | Technician 2 | 38 |
| 24 | 1/11/2023 | Technician 5 | 41 |
| 25 | 1/13/2023 | Technician 2 | 36 |
| 26 | 1/18/2023 | Technician 5 | 35 |
| 27 | 1/19/2023 | Technician 4 | 33 |
| 28 | 1/24/2023 | Technician 4 | 37 |
| 29 | 1/26/2023 | Technician 2 | 34 |
| 30 | 1/31/2023 | Technician 3 | 44 |

Only the samples that meet the criteria defined in the define phase are selected for the measure phase. Thus, only the turnaround time of the samples that contain between 34 and 40 coupons were collected and measured. The turnaround time data was collected by observing the lab technician while they perform the weld inspection. The project team used a stopwatch to record the time of each step in the weld verification process. Then the collected times were inserted into Microsoft Excel and then the collected turnaround time data was calculated using

Minitab software.  Due to the production schedule, customer demand, and samples criteria defined in the Define phase, the project team collected thirty samples within three months of the measure phase. The welding inspections of the collected samples were conducted by different welding lab technicians. The number of lab technicians in the welding lab is ten technicians. However, five lab technicians were excluded from this study. Three of them were excluded because they are team leaders and they perform tasks other than welding inspections, and these tasks interrupt the welding inspection tasks. The other lab technician who was excluded because he was hired recently, and he was under training during the measure phase. Another lab technician was excluded because he quit the work during the project, so the project team decided to exclude the measurement of the samples that were done by this lab technician due to the team will not be able to collect samples from this technician in the Improve phase.

***Lab technician productivity.*** The project team utilized the method used by the welding lab management to measure the productivity of each lab technician in the welding lab. Table 4 contains 30 samples of the productivity percentage for five welding lab technicians.

Table 4

*The productivity of weld lab technician 1,2,3,4, and 5 before the project.*

| Sample # | Technician 1 Productivity | Technician 2 Productivity | Technician 3 Productivity | Technician 4 Productivity | Technician 5 Productivity |
|---|---|---|---|---|---|
| 1 | 62.92% | 56.96% | 53.25% | 35.63% | 101.38% |
| 2 | 75.13% | 64.25% | 54.29% | 51.71% | 65.46% |
| 3 | 80.29% | 46.42% | 74.21% | 39.02% | 71.67% |
| 4 | 90.50% | 70.25% | 44.88% | 42.63% | 93.00% |
| 5 | 91.38% | 68.54% | 39.63% | 41.04% | 76.33% |
| 6 | 80.29% | 63.58% | 72.13% | 39.60% | 71.83% |
| 7 | 81.43% | 56.38% | 61.54% | 42.04% | 77.75% |
| 8 | 93.42% | 54.25% | 69.08% | 58.79% | 84.21% |
| 9 | 80.79% | 71.29% | 71.63% | 33.96% | 77.75% |
| 10 | 77.31% | 57.92% | 56.42% | 57.13% | 84.21% |

| | | | | | |
|---|---|---|---|---|---|
| 11 | 82.10% | 61.21% | 57.83% | 61.13% | 63.46% |
| 12 | 76.54% | 49.00% | 59.79% | 41.46% | 66.08% |
| 13 | 79.69% | 59.30% | 63.00% | 41.63% | 78.67% |
| 14 | 85.38% | 61.83% | 59.79% | 57.13% | 91.50% |
| 15 | 68.84% | 61.90% | 56.17% | 61.13% | 89.92% |
| 16 | 89.00% | 68.63% | 48.84% | 41.46% | 93.38% |
| 17 | 83.92% | 70.21% | 46.63% | 41.54% | 86.42% |
| 18 | 68.84% | 69.88% | 79.88% | 50.58% | 80.25% |
| 19 | 88.58% | 65.67% | 56.13% | 51.50% | 78.67% |
| 20 | 90.79% | 54.21% | 54.54% | 63.79% | 85.71% |
| 21 | 88.83% | 69.54% | 46.67% | 39.25% | 82.92% |
| 22 | 66.63% | 68.67% | 59.75% | 39.63% | 95.83% |
| 23 | 91.48% | 68.80% | 56.50% | 35.96% | 72.88% |
| 24 | 75.67% | 65.04% | 52.19% | 33.58% | 79.50% |
| 25 | 89.70% | 53.33% | 52.75% | 46.50% | 80.49% |
| 26 | 89.70% | 66.46% | 59.50% | 35.76% | 83.79% |
| 27 | 76.82% | 63.71% | 40.58% | 34.83% | 66.42% |
| 28 | 76.82% | 60.21% | 58.42% | 51.67% | 80.08% |
| 29 | 92.00% | 67.04% | 59.04% | 39.04% | 94.00% |
| 30 | 90.92% | 53.33% | 68.09% | 40.46% | 76.93% |

The leader of the Weld Lab collects the productivity data and inserts it into a Microsoft Excel which contains the formula below. The lab technician's productivity is measured by calculating the number of welds archived and the number of welds measured within a single working shift (8 hours). The formula used for this metric is:

Lab technician productivity = (No. of archived welds/600 + No. of measured welds/480) * 8/ No. of worked hours

Where:

600 is the number of welds that must be archived to achieve 100% productivity.

480 is the number of welds that must be measured to achieve 100% productivity.

One of the responsibilities of the welding lab leader is collecting and calculating the productivity of each lab technician. Therefore, the researcher did not collect this data, but the researcher sorted it in one Microsoft Excel sheet. Sixty samples of productivity data were collected for each welding lab technician. These samples are data for three months, which is the same period assigned to collect the turnaround data. Then, only thirty random samples for each welding lab technician were selected. The researcher used a data analysis tool in Microsoft Excel to perform the random sampling.

***Sigma level baseline.*** The DPMO and Sigma level calculation for the turnaround time samples before the project are shown below. The Sigma level was calculated using Microsoft Excel's functions.

No. of failure = 13

No. of samples = 30, therefore

DPMO = (13 / (1 * 30)) *1000000 = 433333.3

Sigma level = (NORM.S.INV (1- (DPMO/1000000))) +1.5 = 1.667894

Based on information given by the welding lab leader, it takes 40 minutes on average to process a welding inspection on product H if the number of welding coupons is between 34 and 40 coupons. Therefore, on average, the turnaround time of the welding verification process is 40 minutes. According to this information, the project team set 40 minutes as the time limit for performing weld inspection on product H with the number of coupons defined above. Thus, any weld inspection exceeding this time limit is considered a failure. In contrast, any weld inspection that takes less than 40 minutes is considered a pass. Based on this rule, the project team calculated the number of failures in the collected turnaround times and the number of failures was 13. Based on the number of failures, the DPMO and sigma level were calculated as shown above.

### Analysis phase

Analyzing the weld verification process determined six improvement opportunities as shown in flowchart in Figure 9. These are non-value-added activities, redundant, or value-added activities but can be improved or streamlined.

The VSM developed in Measure phase shows that archiving, measuring, and reporting results are the main steps in the weld verification process, and these steps are the most time-consuming activities. The total time of these three steps is 36, whereas the total time of the weld verification time is 39 minutes. The time of archiving step depends on the number of weld coupons that need to be achieved. Each weld coupon is placed under a microscope equipped with a camera to capture the cross-section picture of the weld. No improvement could be made on this step due to the limitation of the technique and the software used on this step. The next step is measuring the weld picture. This step is done by drawing measurement lines on the weld cross-section picture using the weld image processing software. Then the software converts the lines pixels into measurements value in millimeters. Improving this step is also limited to the capability of the software. Thus, any further improvement must consider adopting different software.

The last step in the weld verification process is reporting the weld results. This step consists of six activities. All these activities are done using Microsoft Excel spreadsheet. Once the weld measuring is completed, the welding lab technicians extract the weld images, and the weld measurement results on Excel template designed for this purpose. Then lab technicians review the report and perform some editing such as deleting the conforming weld. Only non-conforming weld remains in the weld report to be sent via email to the assembly and quality engineers and technicians. Before emailing the welding report, lab technicians must save a copy of the welding report in folder designated to each product. The next activity is creating a cover sheet for the weld report. The cover sheet contains product information, such as product name, serial number, model, date, and time. Also, the cover sheet consists of a table and each row contains information for a one non-conforming weld. This information is the weld identification number (ID) and the weld status, which describes the failure that made the weld is non-conforming weld. Another important activity in the weld reporting step is updating the welds trend tracker. The trend tracker is an Excel spreadsheet containing the status of all welds. Each Excel spreadsheet is for one product and for one year. Welding lab technicians insert the status of all inspected welds based on the weld’s status in the weld report. The last step is printing the welds status in the cut sheet, which also contains the weld ID and the weld status. Then this document is stored with a copy of the cover sheet in a cabinet drawer.

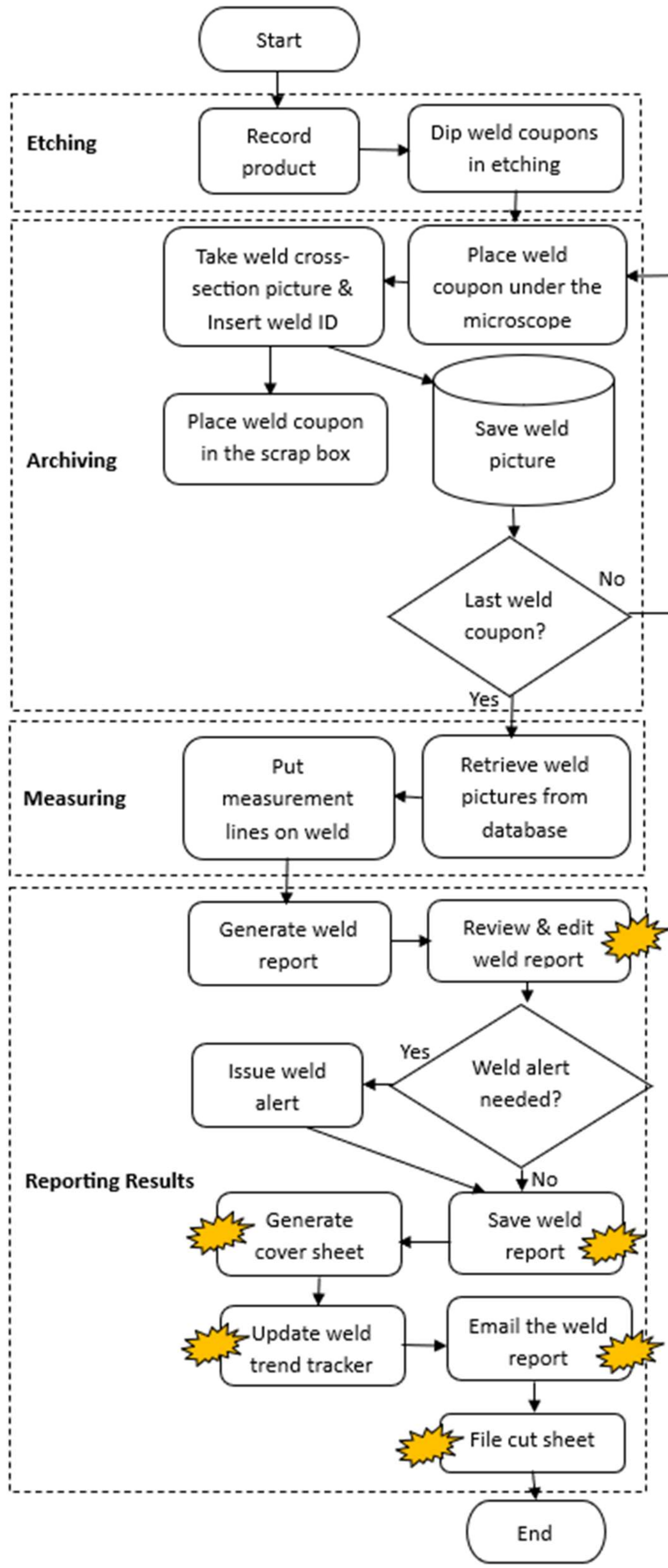



*Figure 9.* Flowchart of the welding verification report before the project.

In view of the preceding, the weld verification process uses three documents other than the welding report, these documents are: report cover sheet, coupons cut sheet, and the welds trend tracker. A separate DVM was created for each of these documents. In the DVM, each section of the document is classified as non-value-added, redundant, customer value added, and operational value added. Any section classified as non-value-added or redundant can be eliminated or reduced. Likewise, any section classified as customer value added or operational value added can be streamlined (see Tables 5, 6, and 7).

Most of the activities within the weld reporting step are done in a non-automated way. For instance, the weld technicians insert the welds' status one by one in the weld trend trackers. This is a time-consuming approach and is a direct cause of variation in the process because the time required for this activity is directly proportional to the number of weld coupons. Likewise, the time required for creating cover sheet increases when the number of nonconforming welds increases. The manual approach of performing the weld reporting step also consists of redundant activities as shown in the Document Value Mapping (DVM). For instance, Job Serial Number (JSN), model, cut type, and weld status are repeated in multiple documents, such as cover sheet, cut sheet and welds' trend tracker.

Table 5

*Cover sheet DVM*

| Document Name: **Cover Sheet** | | | | |
|---|---|---|---|---|
| | **Candidates to Eliminate or Reduce** | | **Candidates for Streamlining** | |
| | **NVA** | **Redundant** | **Customer value added** | **Operational value added** |
| Model | | X | | X |
| ID's cut (no. of cuts) | | | X | X |
| Weld Tech notified | | | | X |
| JSN (Job Serial Number) | | X | | X |

| | | | | |
|---|---|---|---|---|
| Cut Type | | | | X |
| Weld Status | | X | | X |

Table 6

*Cut sheet DVM*

| Document Name: **Cut Sheet** | | | | |
|---|---|---|---|---|
| | **Candidates to Eliminate or Reduce** | | **Candidates for Streamlining** | |
| | **NVA** | **Redundant** | **Customer value added** | **Operational value added** |
| JSN (Job Serial Number) | | | X | X |
| Weld Status | | X | | X |

Table 7

*Trend tracker DVM*

| Document Name: **Trend Tracker** | | | | |
|---|---|---|---|---|
| | **Candidates to Eliminate or Reduce** | | **Candidates for Streamlining** | |
| | **NVA** | **Redundant** | **Customer value added** | **Operational value added** |
| JSN (Job Serial Number) | | X | X | |
| Julian Date | | X | | X |
| Cut Type | | X | | X |
| Weld Status | | X | X | |

The next step in the analyze phase was the statistical and graphical analysis of the data collected during the measure phase. Statistical and graphical analysis were used to help understanding the collected data and identifying the performance deficiency and then identifying ways to eliminate waste and redundancy. Normality tests were performed to verify that the samples were drawn from a normally distributed population (Figure 10). Then control charts were made to verify that the process is stable and under control (Figure 11). The last step was calculating the process capabilities to determine the capability of the weld verification process

(Figure 12). The process capability analysis of the turnaround time before the project shows that the process performance index (Ppk) is less than 1, which means the weld verification process was not capable of meeting the specified requirements. The process performance index (Ppk) and the process performance index (Pp) are not equal; therefore, the process was not centered between the specification limits (Figure 12).

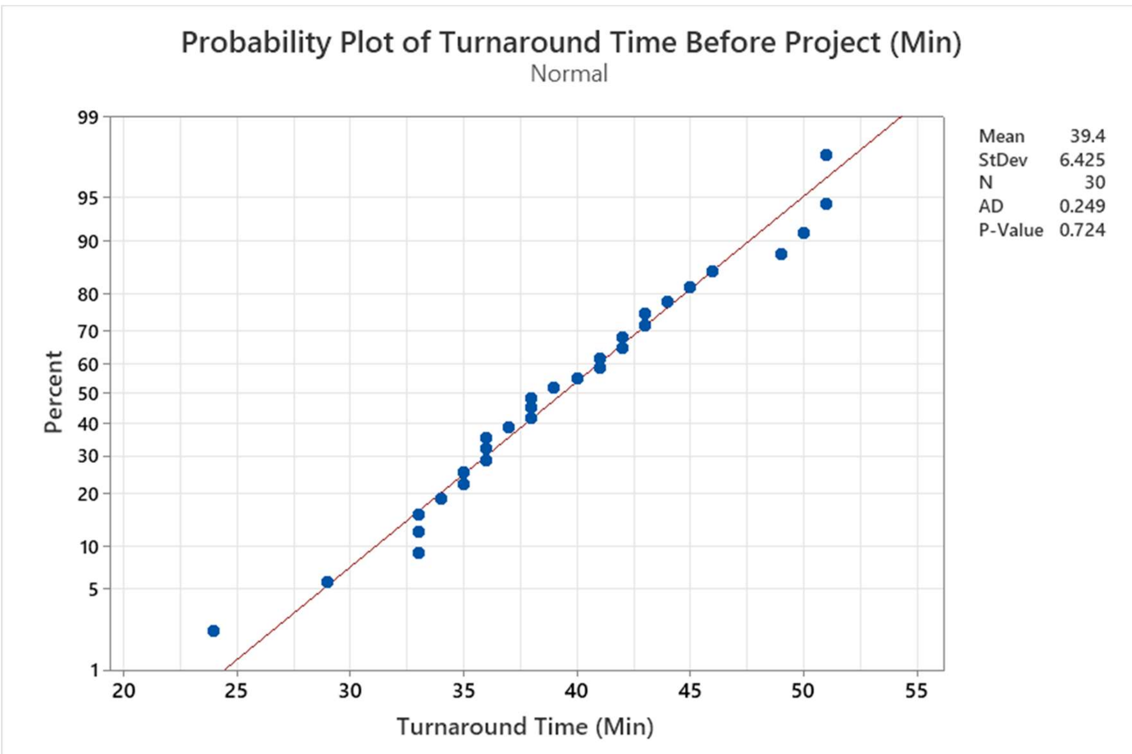



*Figure 10.* Normality test of Turnaround time before the project.

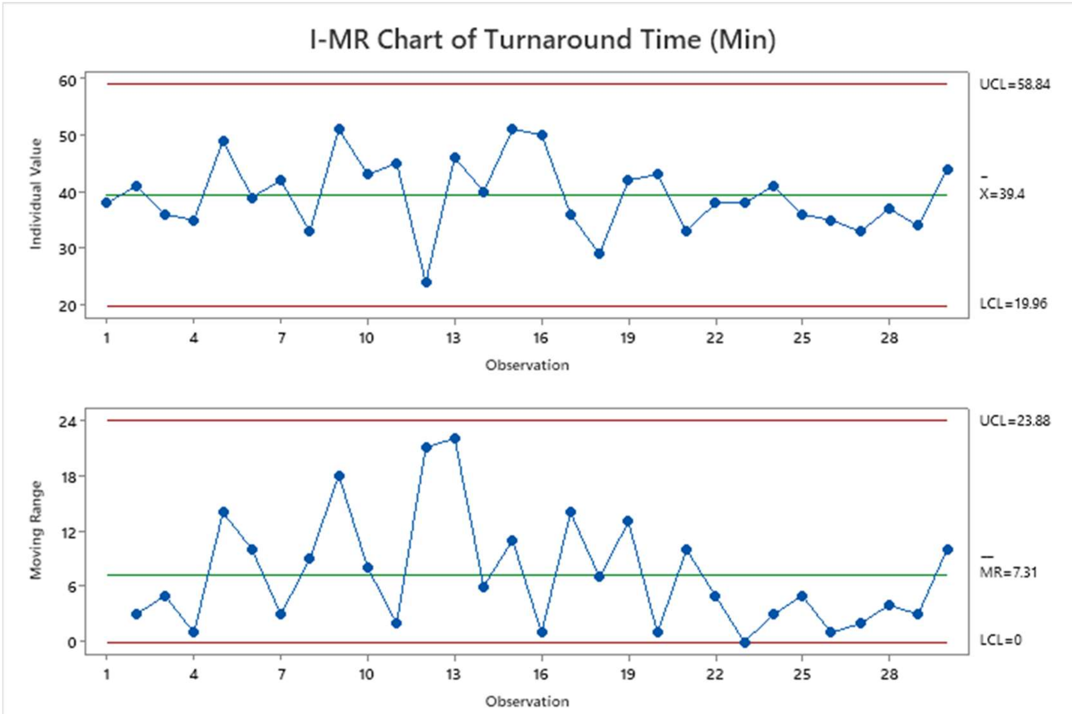



*Figure 11*. Individual and moving ranges chart of Turnaround time before the project.

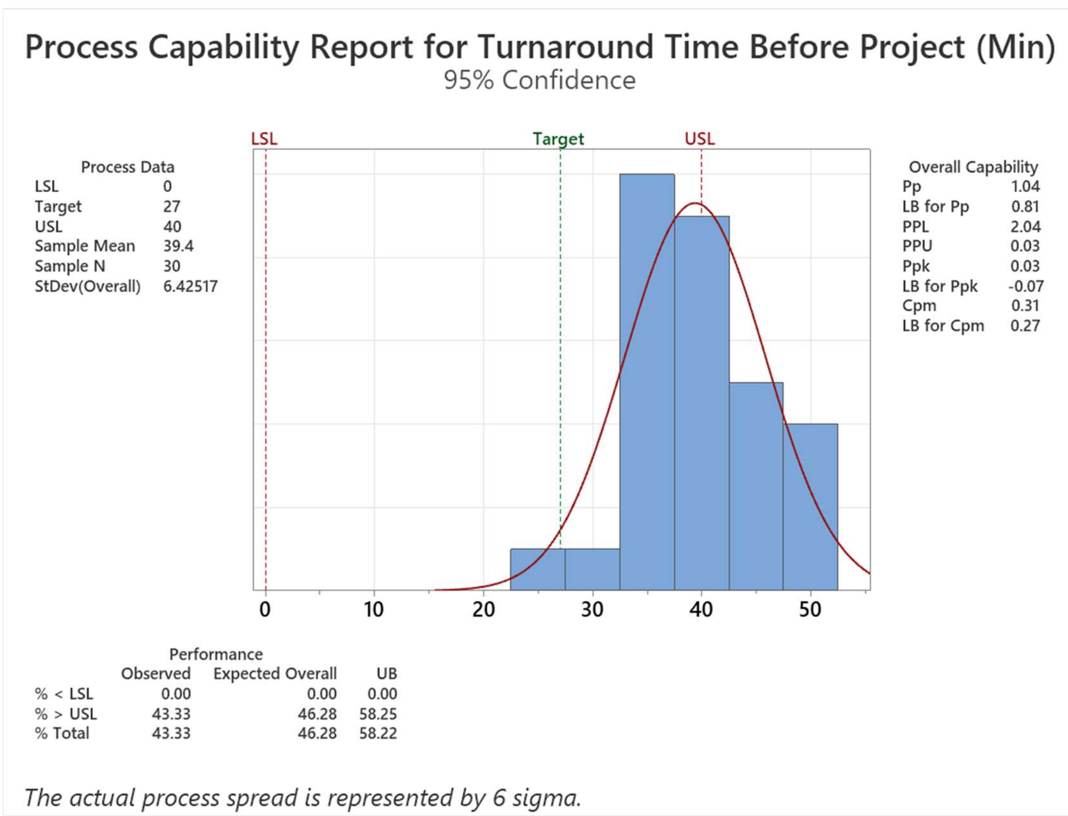



*Figure 12*. Process capability of Turnaround time before the project.

**Improve phase**

The improve phase focused on the reporting results step. Six activities in this step were eliminated or streamlined. A flowchart which describes the welding verification process after implementation of the suggested improvements is shown in Figure 13.

As mentioned in analysis phase, the archive step is very restricted step due to the customer requirements. Furthermore, observing this step during the development of VSM does not show any non-value-added or redundancy involved in this step. The next step that was reviewed by the project team is the weld measuring step. To improve this step, the welding lab needs to use new software with higher features and capabilities due to the current software is simple and providing only the basics image processing features. Therefore, the management of the quality department contacted a research and development (R&D) company which is a sister company and belongs to the same corporation. The R&D company suggested using Artificial Intelligence (AI) to improve this step. The R&D company has started developing new software with AI capabilities to replace the current software. As of the time of writing this research paper, the R&D company collected weld images to create a reference database for the AI software. Some initial testing was conducted, but the estimate completion time of the AI software is in 2025. Therefore, improving the weld measuring step was excluded from this research scope.

The last step in the weld verification process is reporting welding results. Most of the activities within this step are done in a manual approach. The project team suggested replacing the manual approach with a computerized method. The researcher proposed developing Microsoft Excel macros to assist welding lab technicians performing welds reporting step. The proposed macros are good solutions to eliminate redundancy and streamline the weld verification process. Excel's macros also reduce the variation in the process by reducing the time required to perform each task. For example, the difference between creating a cover sheet for ten welds and the time required for twenty welds is very small due to the capability of Excel's Visual Basic for Applications (VBA) to perform this task very quickly. Moreover, Excel's VBA reduces human mistakes and standardizes the process by reducing the human intervention in these activities.

Thus, after obtaining the approval, the researcher collected the information and data required to develop the proposed VBA. Then the researcher developed nine VBA macros to perform the main weld reporting tasks and some other tasks which are helpful for the weld report (see Figure 14). Before implementing the new weld report, the researcher performed User Acceptance Test (UAT) to make sure that VBA works as intended. Once the User Acceptance Test was confirmed and the management approval obtained, the researcher implemented the new macros for all products. By developing the Excels macros using Visual Basic for Application programming language, editing weld report task was eliminated and replaced with an Excel's macros. Filing the cut sheet task was eliminated also because the paper copy was replaced with electronic copy generated by Excel's Visual Basic for Applications (VBA). Generate cover sheet, save weld report, update welds trend tracker, and email weld report tasks were streamlined using Excel's VBA.

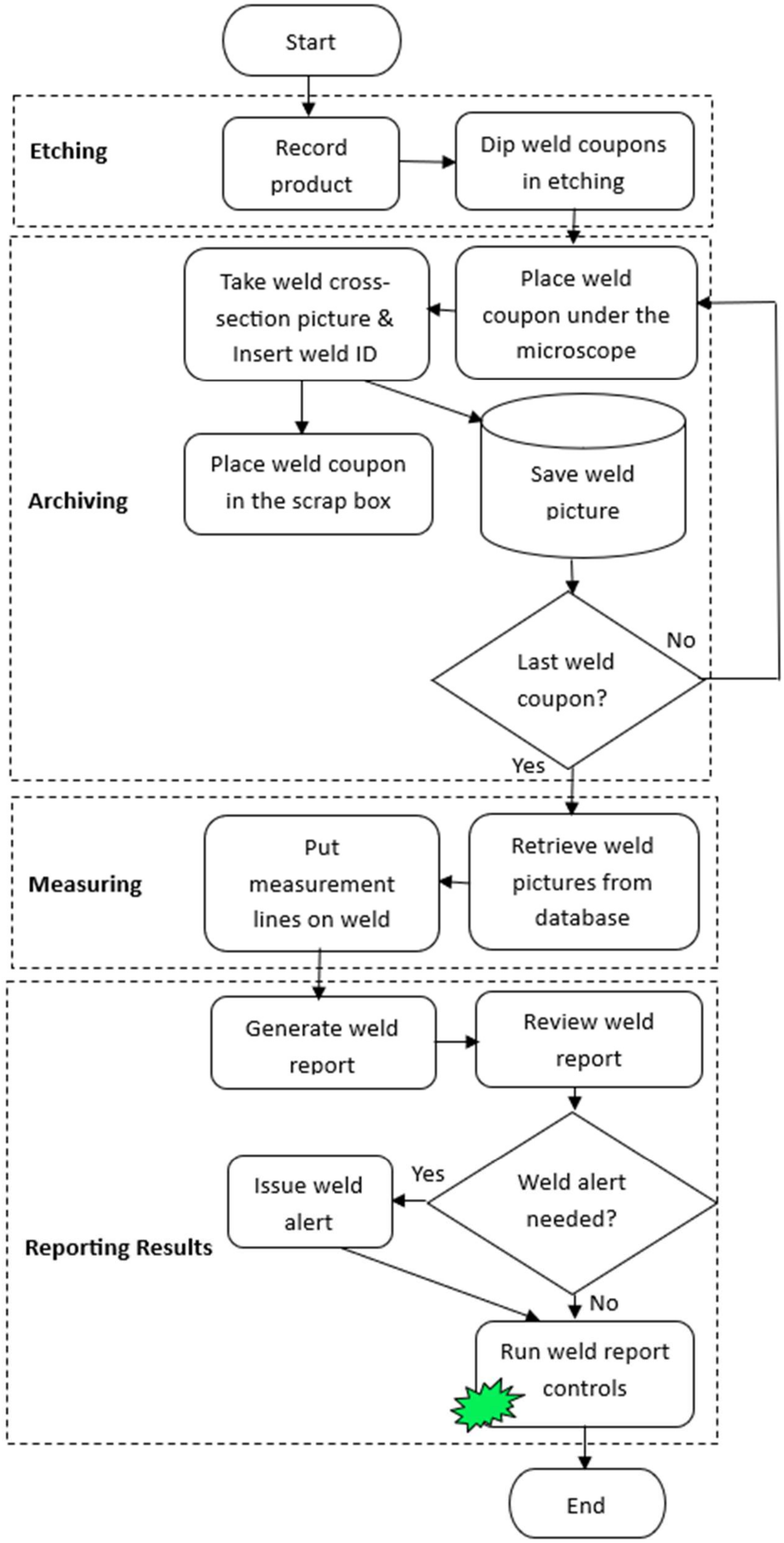



*Figure 13*. Flowchart of the welding verification report after the project.

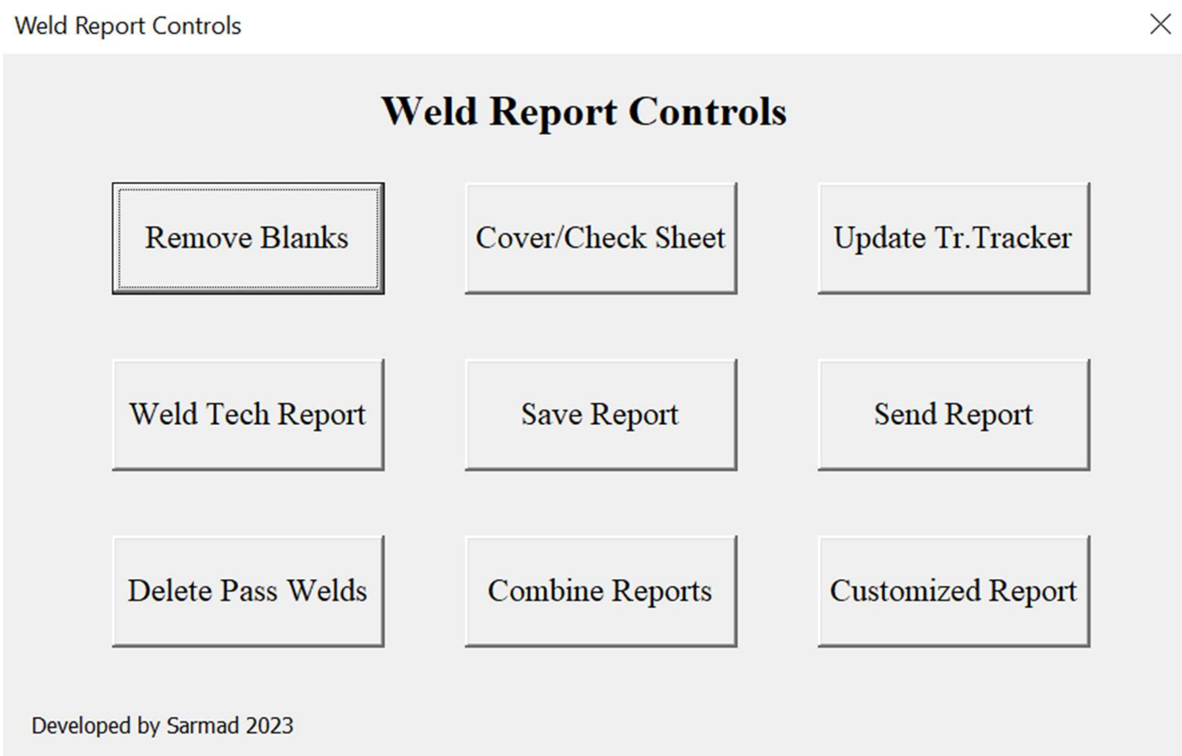



*Figure 14.* Welds report controls developed using Excel's VBA.

The last step in the Improve phase was verifying the improvement by collecting data for the same metrics used in the measure phase. Table 8 presents the turnaround data after the project and Table 9 contains the welding lab technicians' productivities after the project.

Table 8

*Turnaround time for the product H after the project.*

| Sample # | Date | Lab Technician | Turnaround Time (Min) |
|---|---|---|---|
| 1 | 9/13/2023 | Technician 4 | 25 |
| 2 | 9/14/2023 | Technician 3 | 33 |
| 3 | 9/15/2023 | Technician 1 | 35 |
| 4 | 9/19/2023 | Technician 4 | 20 |
| 5 | 9/20/2023 | Technician 5 | 24 |
| 6 | 9/22/2023 | Technician 4 | 28 |
| 7 | 9/26/2023 | Technician 2 | 22 |
| 8 | 9/27/2023 | Technician 3 | 28 |
| 9 | 9/28/2023 | Technician 1 | 33 |

| | | | |
|---|---|---|---|
| 10 | 9/29/2023 | Technician 2 | 28 |
| 11 | 10/3/2023 | Technician 1 | 43 |
| 12 | 10/4/2023 | Technician 4 | 29 |
| 13 | 10/5/2023 | Technician 5 | 32 |
| 14 | 10/10/2023 | Technician 2 | 28 |
| 15 | 10/11/2023 | Technician 3 | 21 |
| 16 | 10/12/2023 | Technician 3 | 33 |
| 17 | 10/13/2023 | Technician 5 | 28 |
| 18 | 10/17/2023 | Technician 1 | 27 |
| 19 | 10/19/2023 | Technician 4 | 28 |
| 20 | 10/20/2023 | Technician 2 | 44 |
| 21 | 10/24/2023 | Technician 1 | 34 |
| 22 | 10/25/2023 | Technician 4 | 36 |
| 23 | 10/26/2023 | Technician 5 | 26 |
| 24 | 10/27/2023 | Technician 3 | 38 |
| 25 | 10/31/2023 | Technician 2 | 31 |
| 26 | 11/1/2023 | Technician 5 | 23 |
| 27 | 11/2/2023 | Technician 1 | 41 |
| 28 | 11/3/2023 | Technician 5 | 42 |
| 29 | 11/8/2023 | Technician 3 | 27 |
| 30 | 11/9/2023 | Technician 2 | 25 |

Table 9

*The productivity of welding lab technician 1,2,3,4, and 5 after the project.*

| Sample # | Technician 1 Productivity | Technician 2 Productivity | Technician 3 Productivity | Technician 4 Productivity | Technician 5 Productivity |
|---|---|---|---|---|---|
| 1 | 90.00% | 93.71% | 102.30% | 61.88% | 82.21% |
| 2 | 98.00% | 79.54% | 81.79% | 104.63% | 87.00% |
| 3 | 84.33% | 77.46% | 95.54% | 70.13% | 87.42% |
| 4 | 99.04% | 90.75% | 79.79% | 74.04% | 97.21% |
| 5 | 102.75% | 72.54% | 108.67% | 76.96% | 83.17% |
| 6 | 104.97% | 75.17% | 87.41% | 84.75% | 88.92% |
| 7 | 99.04% | 96.50% | 74.58% | 80.00% | 97.71% |
| 8 | 101.96% | 75.63% | 88.58% | 79.50% | 109.79% |
| 9 | 101.96% | 94.04% | 92.38% | 79.63% | 92.21% |
| 10 | 102.13% | 75.17% | 81.96% | 78.58% | 102.14% |
| 11 | 91.67% | 75.21% | 71.21% | 99.92% | 83.38% |
| 12 | 106.88% | 75.29% | 83.67% | 70.83% | 91.38% |
| 13 | 96.75% | 91.75% | 86.63% | 74.33% | 88.39% |
| 14 | 96.25% | 96.50% | 83.58% | 69.88% | 81.29% |

| | | | | | |
|---|---|---|---|---|---|
| 15 | 97.97% | 89.02% | 82.29% | 78.29% | 91.00% |
| 16 | 90.40% | 82.83% | 95.63% | 91.04% | 96.17% |
| 17 | 88.96% | 72.96% | 84.42% | 95.63% | 85.33% |
| 18 | 99.08% | 94.38% | 73.17% | 76.75% | 83.58% |
| 19 | 104.13% | 81.21% | 93.00% | 102.33% | 83.79% |
| 20 | 97.21% | 82.38% | 78.42% | 90.46% | 105.96% |
| 21 | 94.67% | 80.75% | 81.92% | 87.38% | 114.67% |
| 22 | 89.29% | 82.38% | 84.92% | 87.50% | 89.71% |
| 23 | 103.88% | 81.00% | 90.50% | 99.50% | 106.42% |
| 24 | 111.04% | 77.63% | 79.79% | 81.46% | 93.58% |
| 25 | 112.00% | 84.52% | 80.63% | 99.17% | 101.00% |
| 26 | 107.96% | 84.00% | 78.71% | 86.50% | 83.23% |
| 27 | 87.54% | 77.29% | 83.54% | 102.33% | 89.67% |
| 28 | 100.07% | 78.04% | 90.08% | 89.50% | 92.04% |
| 29 | 89.29% | 73.25% | 82.92% | 95.25% | 94.63% |
| 30 | 108.46% | 77.13% | 81.67% | 107.33% | 103.42% |

After collecting the turnaround time and the welding lab technicians' productivity data, statistical and graphical analysis were performed to validate the improvements. The statistical and graphical analysis are shown in Figures 15, 16, and 17. The process capability analysis of the turnaround time after the project shows that the process performance index (Ppk) is still less than 1, which means the welding verification process is not capable of meeting the specified requirements. The process performance index (Ppk) and the process performance index (Pp) are not equal; therefore, the process is not centered between the specification limits (Figure 17).

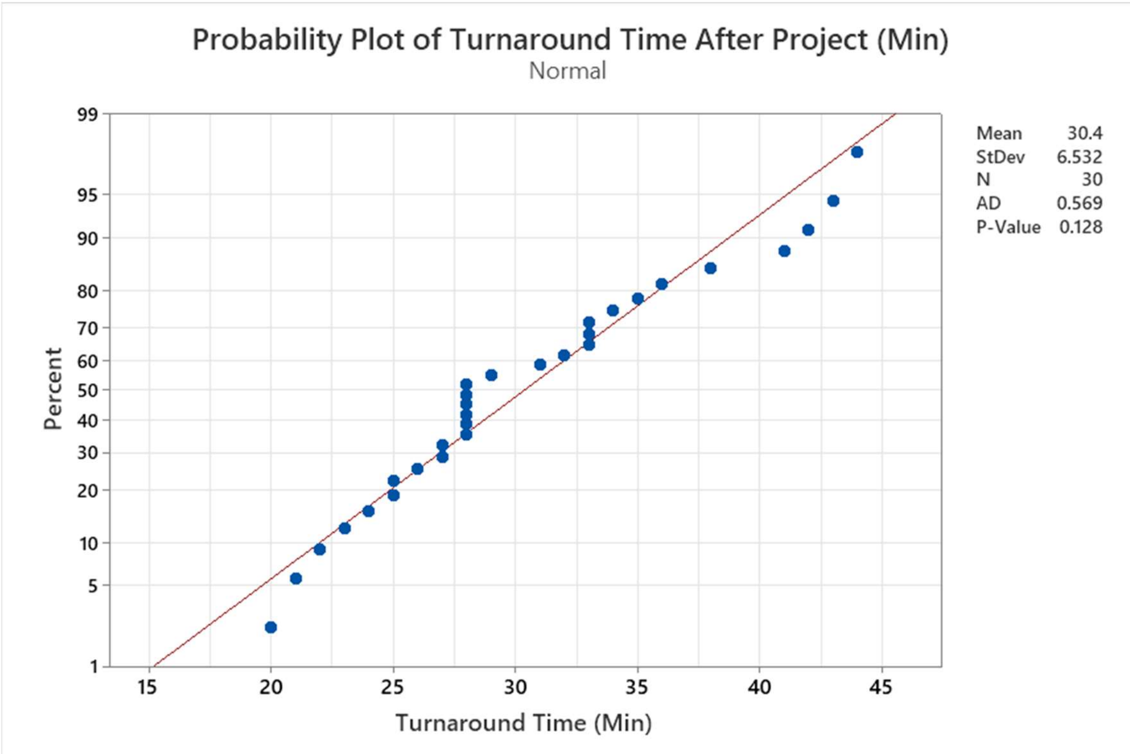



*Figure 15.* Normality test of Turnaround time after the project.

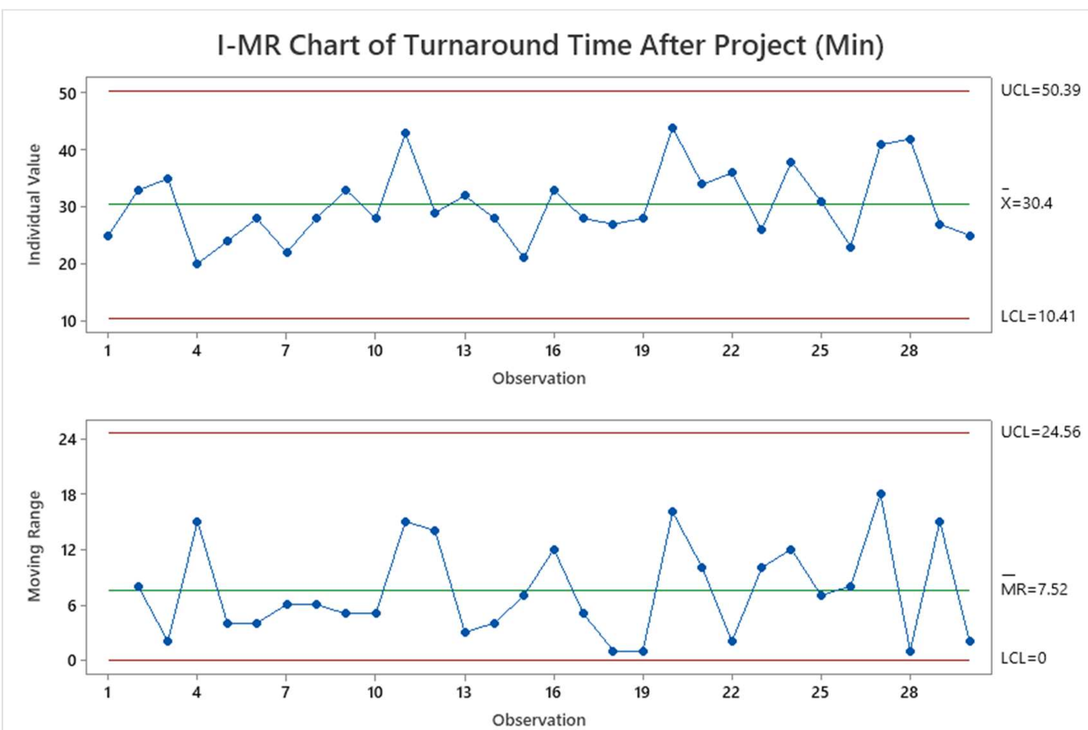



*Figure 16.* Individual and moving ranges chart of Turnaround time after the project.

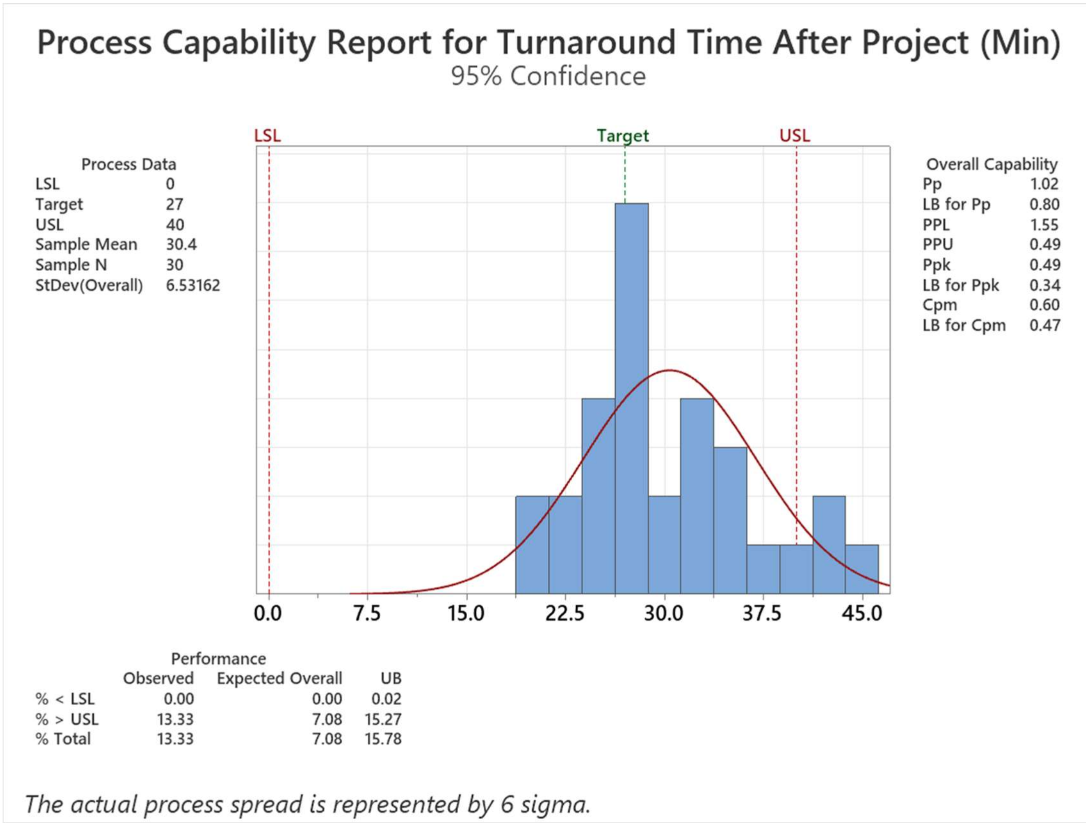



*Figure 17.* Process capability of Turnaround time after the project.

To illustrate the process after the improvements, the project team developed the future state of the VSM map (Figure 18).

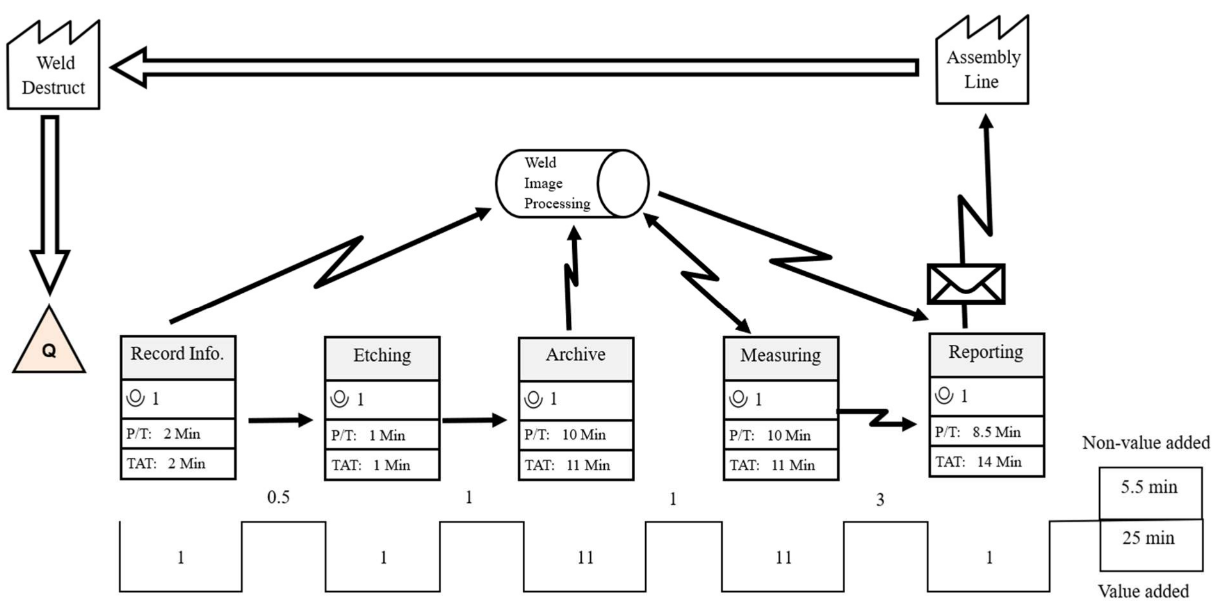



*Figure 18*. Future state of weld verification value stream mapping.

**Statistical and graphical analysis**

All the improvements implemented during the Improve phase were done in the reporting welding results step. Thus, the team performed a statistical and graphical analysis for this step. The graphs below show the process capabilities of this step before and after the project (Figures 19 and 20). Due to the big improvement achieved in this step, the upper control limit for the process capability was changed from 10 minutes to 2 minutes (120 seconds) to make the histogram and the curve in the graph more evident.

The interpretation of the process capability analysis of reporting weld results before and after the project is below:

- The process capability analysis of reporting welds results step before the project shows that the process performance index (Ppk) is less than 1 (Figure 19), which means reporting welding results step was not capable of meeting the specified requirements. The process performance index (Ppk) and the process performance index (Pp) are not approximately equal; therefore, the process was not centered between the specification limits (Figure 19).

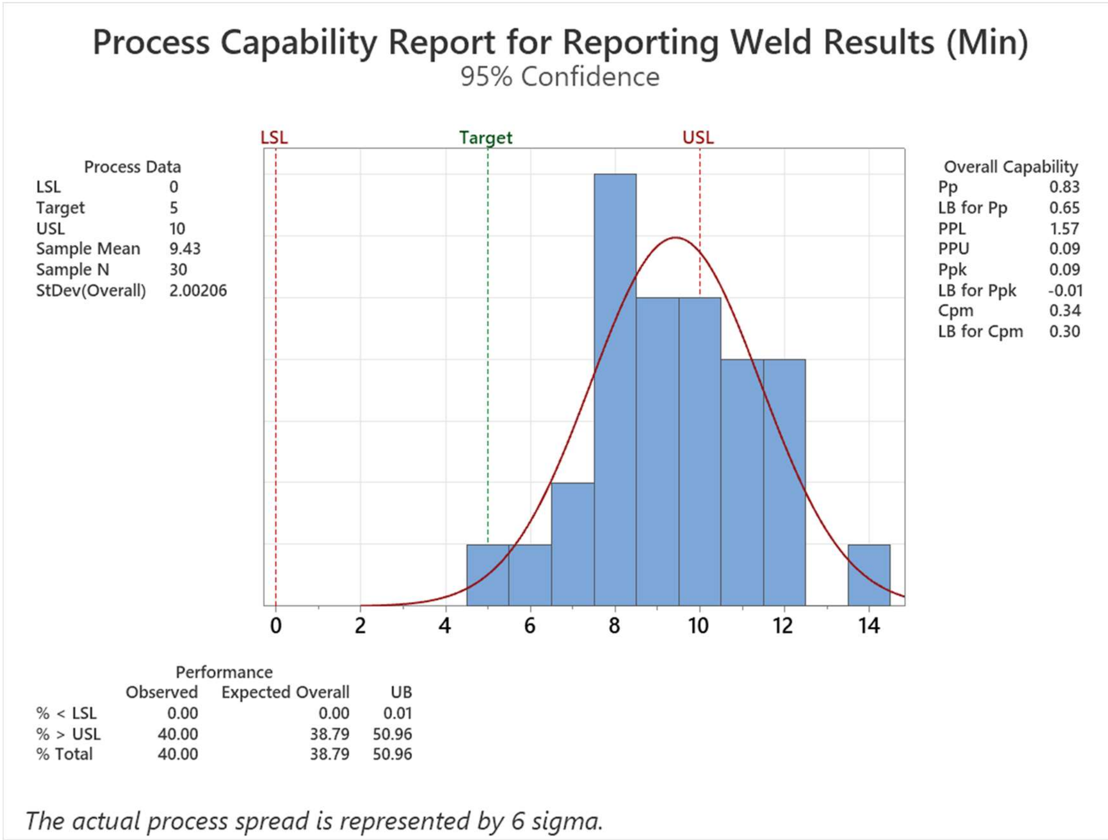



*Figure 19*. Process capability for reporting weld results before the project.

- The process capability analysis of reporting welds results step after the project shows that the process performance index (Ppk) is greater than 1 (Figure 20), which means the welding verification process can meet the specified requirements. The process performance index (Ppk) and the process performance index (Pp) are approximately equal; therefore, the process is centered between the specification limits (Figure 20).

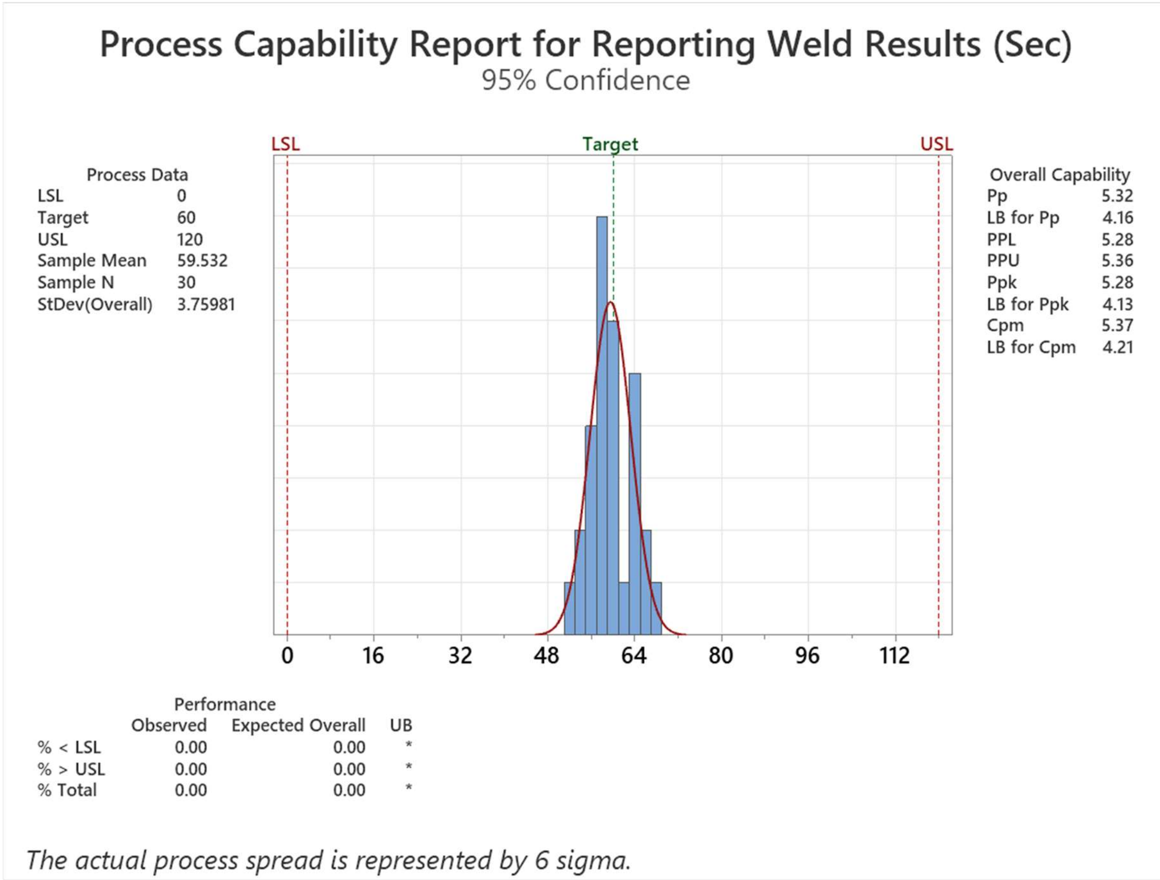



*Figure 20.* Process capability for reporting weld results after the project.

***Turnaround time.*** According to the individual control chart shown below, the maximum turnaround time before the implementation of this project was 51 minutes, and the average time was 39.4 minutes. Whereas the maximum turnaround time after the implementation of the project is 44.2 minutes, and the average turnaround time is 30.4 minutes (Figure 21).

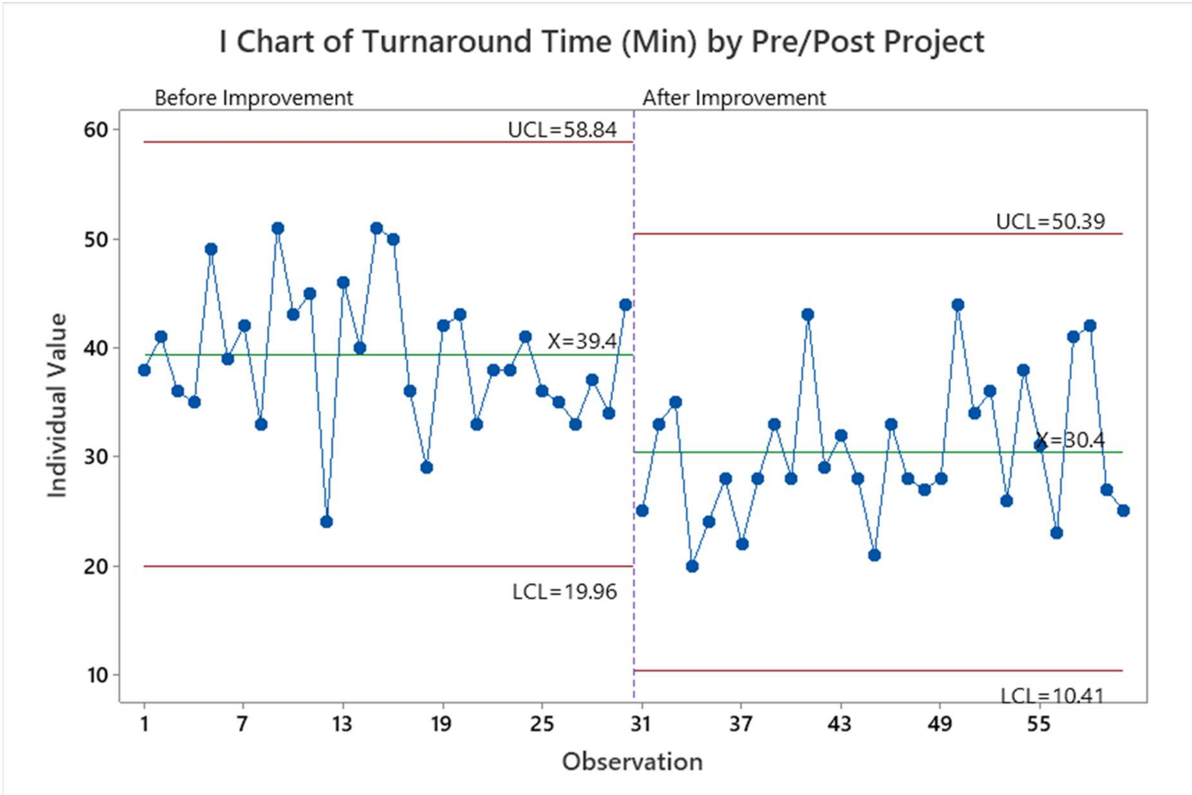



*Figure 21.* I Chart for the turnaround time before and after the project.

***Welding lab technicians' productivity***. Productivity data of five welding lab technicians for before and after the implementation of the project were collected and analyzed. The analysis shows that the productivity for the five lab technicians increased (Figures 22, 23, 24, 25, and 26). The average productivity for lab technicians 1, 2, 3, 4 and 5 increased by 16.4%, 20.1%, 27.55%, 40.86%, and 11.86% respectively. Also, the data shows that the increment percentage is uneven. For instance, the productivity of lab technician 4 increased by 40.86%, whereas the productivity of the lab technician 5 increased by only 11.86%. The collected data does not explain the cause of this variation. To address this variation, a project focusing on the variation of welding lab technicians' performance is needed.

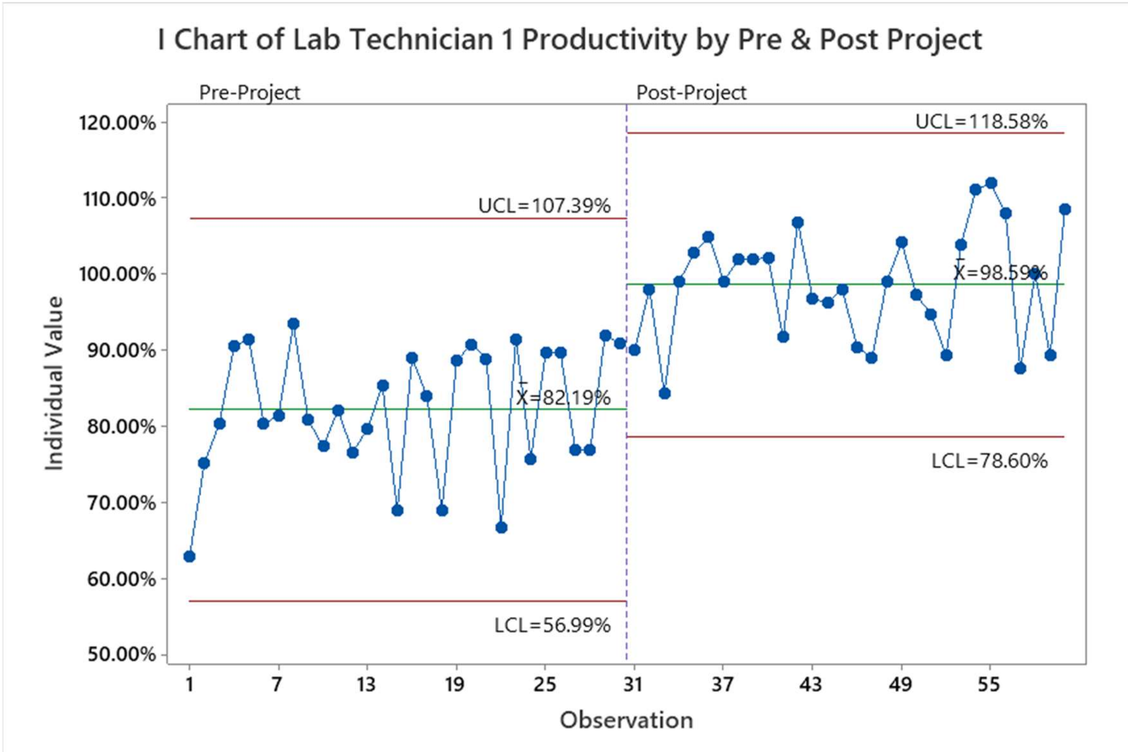



*Figure 22.* I Chart for the lab technician 1 before and after the project.

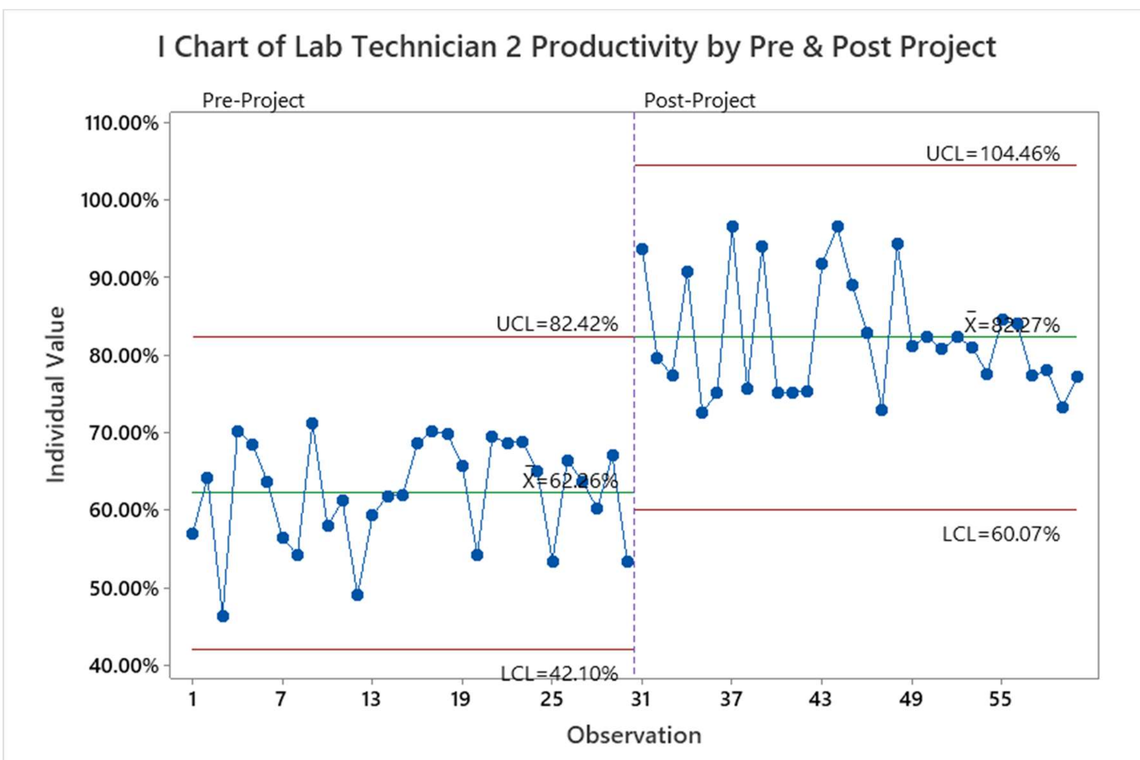



*Figure 23.* I Chart for the lab technician 2 before and after the project.

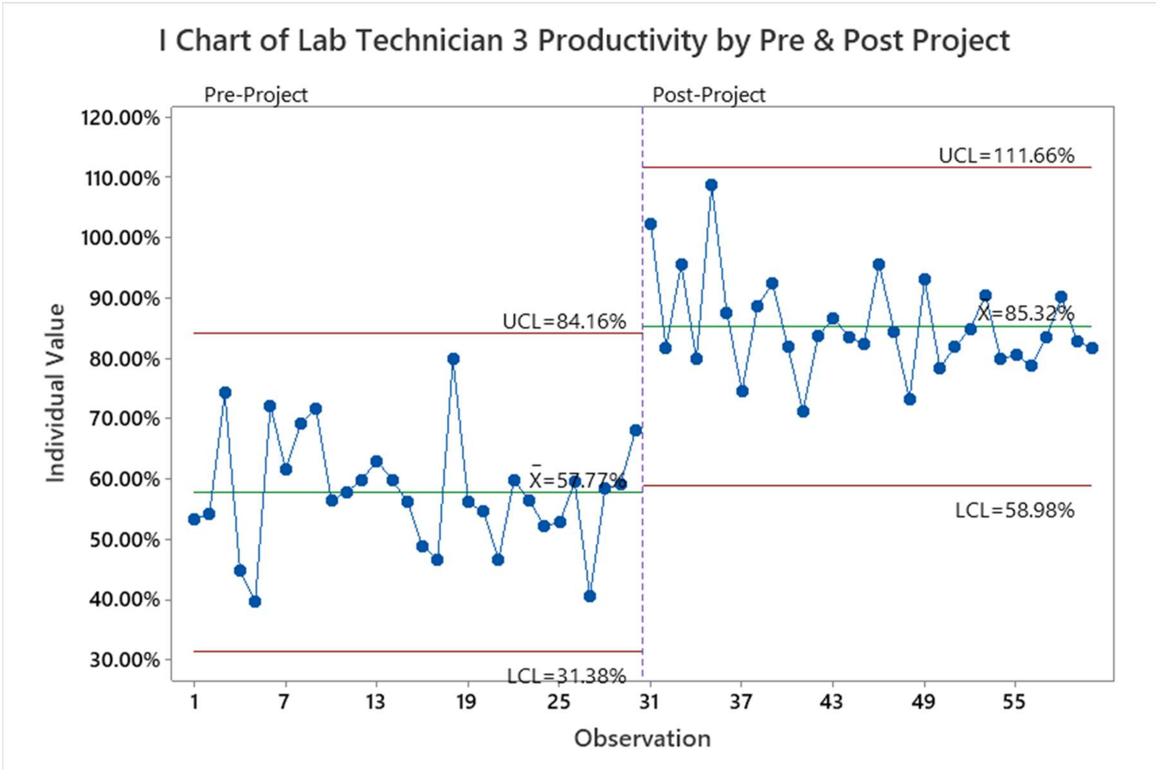



*Figure 24.* I Chart for the lab technician 3 before and after the project.

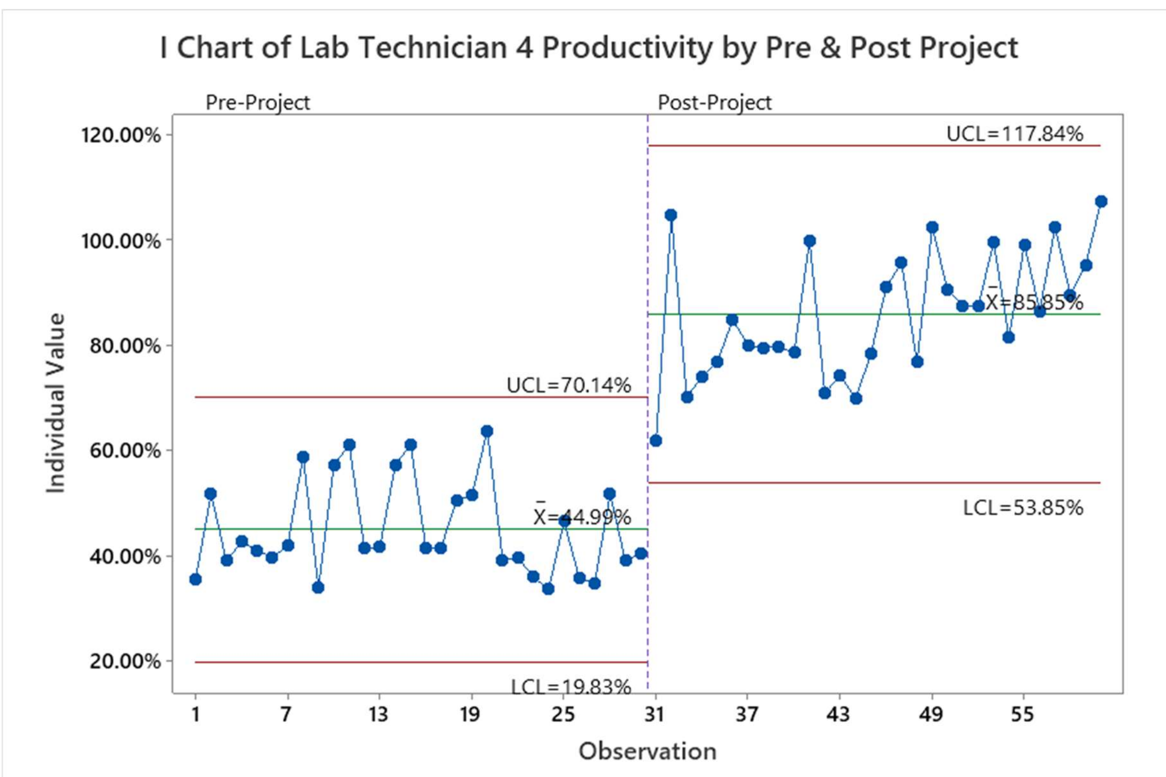



*Figure 25.* I Chart for the lab technician 4 before and after the project.

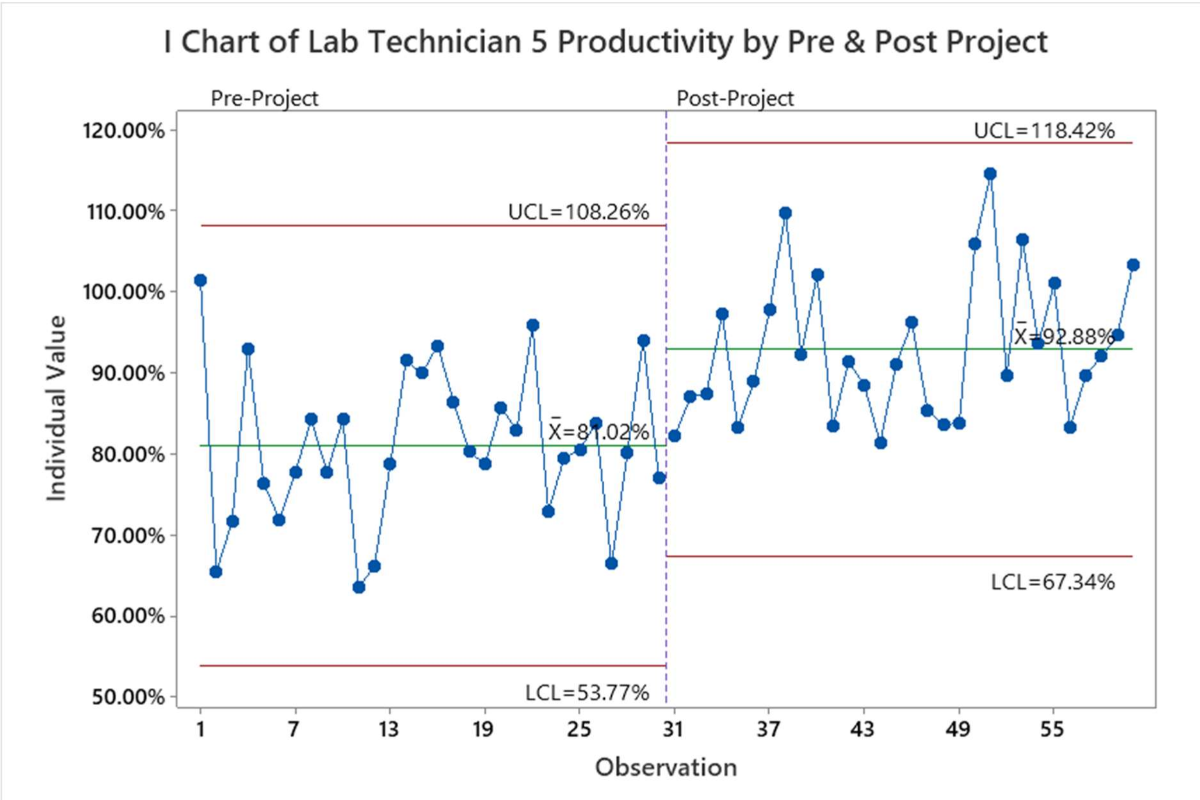



*Figure 26.* I Chart for the lab technician 5 before and after the project.

***Sigma level*.** The third metric used in this study is the sigma level. The collected data after the project shows that the number of failures was 4. The number of failures was calculated based on the rule set by the project team in coordination with Weld Lab management. The rule considers the turnaround time of weld verification task that exceeds 40 minutes is a failure. According to the number of failures, the DPMO is 133333.33, thus the sigma level of the after project is 2.61, which means that the sigma level of the welding verification process approximately increased by about 1 sigma level. The calculations of DPMO and Sigma level are below. The Sigma level was calculated using Microsoft Excel's functions.

No. of failure = 4

No. of samples = 30, therefore

DPMO = (4 / (1 * 30)) *1000000 = 133333.3

Sigma level = (NORM.S.INV (1- (DPMO/1000000))) +1.5 = 2.610772

**Control phase**

To sustain the improvements of the weld verification process and ensure that the new process will not deviate from the target, the researcher developed Visual Basic for Applications (VBA) codes to record the processing time of all the reporting welds results activities and the turnaround time. The recorded time will be used to create control charts which will be used to monitor the welding verification process performance. Another way to sustain the improvement is by documenting the DMAIC phases as well as the programming documentation. To provide documentation of the Visual Basic for Applications (VBA) programming codes, the researcher (the programmer) provided the Weld Lab management with documentation for all the Visual Basic for Applications (VBA) codes used to develop the Excel's macros.

# Chapter Five

## Conclusion

The implementation of DMAIC approach used in this study aided the researcher to identify and eliminate the waste and redundancy within the welding verification process in the welding laboratory of the company M. Moreover, the researcher reduced the turnaround time of the welding verification process and increased the overall Weld Lab productivity. The project results show that the turnaround time was reduced by 22.84%, where the average turnaround time before the project was 39.4 minutes, and the average turnaround time after the project became 30.4 minutes. Thus, implementing Lean Six Sigma can reduce the turnaround time of the welding verification process.

The reporting welds results step was improved where the samples' mean time of this step before the project was 9.43 minutes, whereas the samples' mean time after the project is less than one minute, 59.53 in specific. Even though the improvement of the reporting welds results step was significant, the process capability index of the turnaround time shows that the welding verification process after the implementation of this project became more capable of meeting the specified requirements. However, the weld verification process is not capable of meeting the specified requirements. The Ppk value before the project was 0.03, which means the process was not able to meet the specified requirements. The Ppk value after the project was improved to 0.49, which means the welding verification process still cannot meet the specified requirements. Thus, Lean Six Sigma can improve the performance of the Weld Lab process; however, the improvement was not adequate to make the weld verification process capable of meeting the specified requirements.

The Individual Charts of the productivity of five welding lab technicians show that the productivity percentage of those lab technicians increased, however the increments were not even for all lab technicians. The productivity increments were 16.4%, 20.1%, 27.55%, 40.86%, and 11.86%. These increments prove that overall productivity of the welding lab increased.

The calculation of sigma level shows that the sigma level was increased by about 1 sigma level. The sigma level of the pretest data was 1.66 and the sigma level of the posttest became 2.61. Conducting a project to implement DMAIC in the Weld Lab at M company did not lead to a higher increase in sigma level due to the achieved improvements been limited to the reporting welds results only. Assigning more time and money to develop new software or adopt new technologies such as Artificial Intelligence (AI) might lead to achieving a significant increase in sigma level.

In addition to the results above, the project streamlined the reporting weld results step by computerizing the activities of this step. This achievement reduced the human intervention in this step, which in turn reduced the variation within this step. Furthermore, computerizing this step using Excel’s macros standardized the activities of the reporting welds results step, which in turn reduces errors made by human mistakes.

The achieved improvements would reflect on the product and process quality. The reduction in the turnaround time would lead to early detection of weld defects to avoid shipping defective products to the customers, which in turn reduces the number of defective products in the WIP and reduces the rework needed to correct those products.

**Recommendations for Future Research**

1. Welds archiving and weld measuring steps were excluded from this study due to the limitations of resources assigned for this study. Thus, future research could include analyzing and improving these steps. Improving these steps would increase the sigma level and might increase the process capability.
2. There was variation in the increased percentage of the lab technicians' productivity. The lab technicians' productivity is affected by different factors such as technicians' skills and experience. Investigating these factors was not part of this project scope. Therefore, future research is recommended to investigate the root causes of lab technicians' productivity variation.

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## Appendix A

Weld Lab Project Charter

| | | | |
|---|---|---|---|
| ***Business unit*** | Quality | ***Product or Service Impacted*** | Weld Verification |
| ***Project Leader*** | Sarmad Al Hilli | ***Deployment Champion*** | T. J, Quality Department Leader |
| ***Green belt*** | P. S | ***Black Belt*** | L. M |
| ***Start Date*** | 10/17/2022 | ***Target Completion Date*** | 7/17/2023 |

<table>
<tr><th>Element</th><th>Description</th><th colspan="5">Team Charter</th></tr>
<tr><td>1. Process</td><td>The process in which opportunity exists.</td><td colspan="5">The Weld lab process that starts with receiving weld coupons and ends with sending the report and updating the tracker.</td></tr>
<tr><td>2. Project Description: what is the “Practical Problem”</td><td>Problem and goal statement (project’s purpose)</td><td colspan="5">Problem statement: Weld Lab struggles to handle excessive workload to provide precise weld verification results in a timely manner. The current capability of the weld Lab area is limited, where there are untapped opportunities to improve performance.<br>Goal statement: The goal is to optimize the Weld Lab process by reducing the turnaround time of the weld testing process by identifying and eliminating wastes and redundancy involved in the process. A lengthy process has a negative on the number defective parts in WIP, and on-time deliveries.</td></tr>
<tr><td rowspan="4">3. Objective:</td><td rowspan="4">What improvement is targeted and what will be the impact on critical business metrics?</td><td>Metric</td><td>Baseline</td><td>Goal</td><td>Entitlement</td><td>Unit</td></tr>
<tr><td>Metric 1:<br>TAT</td><td>40</td><td>20</td><td>20</td><td>Min.</td></tr>
<tr><td>Metric 2:<br>Lab Tech. productivity</td><td>70</td><td>90</td><td>100</td><td>%</td></tr>
<tr><td>Metric 4:<br>DPMO & б Level</td><td>1.6</td><td>4</td><td>5</td><td>б</td></tr>
<tr><td>4. Benefits</td><td>In addition to the cost savings, describe the potential benefits from this project.</td><td colspan="5">Better staff utilization, on-time shipments delivery, and increase customers’ satisfaction</td></tr>
<tr><td>5. Team members:</td><td>List the names and job responsibilities of the members of your team.</td><td colspan="5">S. T, Weld Verification Area Leader<br>E. C, Weld Lab Team Leader<br>M.K, Weld Lab Technician<br>N. L, Continuous Improvement Coordinator</td></tr>
<tr><td rowspan="2">6. Schedule:</td><td rowspan="2">Give the key milestones/dates.</td><td colspan="2">Project Start</td><td colspan="3">10/17/2022</td></tr>
<tr><td colspan="2">“M” Completion</td><td colspan="3">1/31/2023</td></tr>
</table>

| | | | |
|---|---|---|---|
| | M-Measurement<br>A- Analysis<br>I- Improve<br>C- Control | "A" Completion | 3/10/2023 |
| | | "I" Completion | 9/8/2023 |
| | | "C" Completion | 11/17/2023 |
| | | Project Completion | 11/24/2023 |
| **7. Support required**: | Do you anticipate the need for any special capabilities, hardware, trials, etc? | Will be determined during Analysis phase | |

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Keywords (3-5 keywords not included in the title that uniquely describe content): Reduce turnaround time, Increase productivity,Welding Lab

Committee Chair: Dr. John Khouryieh

Additional Committee Members: Dr. Osama E. Mansour Dr. Fatemeh (Mahtab) Orooji

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