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The application of Lean Principles to mitigate greenhouse gas emissions in an automotive industry

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Abstract

A common factor for industrial production is energy, and the level of energy consumed is typically used to measure the growth and economic development of countries. However, as the industrial sector expands and makes efforts to gain competitive advantage, there is a growing concern regarding energy consumption and the ecological burden related to energy use.

Thus far, industry has relied on the Lean manufacturing paradigm to gain the contemporary benefits of profitability, flexibility, and increased efficiency. More recently, the association of Lean manufacturing and environmental impacts has grown in both the industrial and academic fields.

The main aim of this research is to investigate the correlation between lean tools and their effect on Green House Gas emissions, ultimately measuring environmental performance. The research is quantitatively based and entails the study of a weld process production line at Toyota South Africa Motors. The environmental impacts of the production process were observed and measured before and after the implementation of three lean tools: Value Stream Mapping (VSM), Total Productive Maintenance (TPM) and Standardized Work.

Comparing the outcomes, the study found significant differences in the pre-test and post-test of each lean technique applied. VSM allows one to visualize and magnify the environmental performance of the process, which allows for simple quantifying of environmental metrics. TPM brings to light that equipment that is regularly maintained to operate at optimum condition reduces non-value adding energy usage. However, in contrast, Standardized Work has shown minimal benefits within the context of this research.

The findings of this research are beneficial as they contribute to gaining a better understanding of the way lean tools affect environmental performance. While the study contributes to the current body of knowledge, it can also enlighten Small to Medium Enterprises, practitioners and larger organizations to rethink current strategy and allow for simultaneous implementation of Lean Green operations.

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Declaration by Candidate

I, Keshav Ramsunder, declare that unless otherwise indicated, this dissertation is my original work and that it has not been submitted for any degree at another tertiary institution.

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Contents

List of Acronyms

CO2	Carbon Dioxide
ESER	Energy saving and emissions reduction
E-VSM	Environmental value stream mapping
GDP	Gross domestic product
GHG	Greenhouse gas
GMAW	Gas metal arc welding
IMV	International multipurpose vehicle
JIT	Just-in-time
LCA	Life cycle analysis
LESER	Lean energy saving and emissions reduction
N WORK	Necessary Work
NVA	Non-value adding work
OECD	Organization for Economic Co-operation and Development
OEM	Original equipment manufacturer
SMED	Single minute exchange of die
TCP	Toyota Chassis Plant
TPM	Total productive maintenance
TPS	Toyota Production Systems
TSAM	Toyota South Africa Motors
VA	Value adding work
VSM	Value stream mapping

Glossary of Terms

3R	A principle of reducing waste, reusing and recycling resources and products.
5S	A methodology for organizing, cleaning, developing and sustaining a productive work environment.
7 Wastes	Seven wasteful activities identified under the lean manufacturing system.
Andon	A tool that is used to inform and alarm workers of problems within their production process.
Autonomous maintenance	A maintenance strategy where machine operators continuously monitor their equipment, make adjustments and perform minor maintenance tasks on their machines.
Batch build	A method of manufacturing where the products are made as specified groups or amounts, within a time frame.
Carbon footprint	The amount of greenhouse gases released into the atmosphere by a particular human activity.
Cellular manufacturing	A methodology that groups employees, machines and materials into a semi-circle or U-shape layout to produce a given product or product type.
Continuous improvement	A concept that makes an ongoing effort to improve products, services or processes. These efforts can seek ’incremental’ improvement over time or ’breakthrough’ improvement all at once.

Cycle time	The total time taken from the beginning to the end of the process.
Eco-efficiency	A concept of creating more goods and services while using fewer resources and creating less waste and pollution.
Eco-innovation	All forms of innovation activities aimed at significantly improving environmental protection.
Emission factor	A coefficient which allows activity data to be converted into GHG emissions.
Environmental Management Systems	A set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency.
Gas metal arc welding	A welding process which joins metals by heating the metals to their melting point with an electric arc and the arc is struck between a continuous, consumable bare electrode wire and the work piece.
Green manufacturing	The creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, are economically sound, and safe for employees, communities and consumers.
Green paradigm	A theoretical framework that allows for Green manufacturing influences to create sustainable business.

Greenhouse gas	A gas in Earth’s atmosphere that traps heat. It lets sunlight pass through the atmosphere, but they prevent the heat that the sunlight brings from leaving the atmosphere.
Inert gas	A gas that does not undergo chemical reactions under a set of given conditions and which is often used in welding applications.
INSPECTION	A quality check procedure built into the manufacturing process of the Auxiliary Cross member before it is shipped to the next stage.
ISO 14001	An internationally agreed standard that sets out the requirements for an environmental management system.
Just-in-time	A concept that controls inventory and material flow throughout the entire organization. The philosophy involves providing the required part, in the correct quantity at the exact point in time.
Kaizen	A Japanese term meaning continuous improvement.
Kanban	A Japanese word meaning ’card’ or ’visible record’ that refers to cards used to control the flow of production through an organization. It signals the manufacture and supply of components.
Lead time	The amount of time between the initiation of some process and its completion or the elapsed time

	between the receipt of a customer order and filling it.
Lean and Green paradigm	A framework where principles of lean and green manufacturing can be used together to gain efficient and sustainable production.
Lean manufacturing	A methodology that focuses on minimizing waste within manufacturing systems while simultaneously maximizing productivity.
Life cycle analysis	A method used to evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling and final disposal.
LWR X NUT	A weld procedure within the Auxiliary Cross member manufacturing process. This process entails the assembly and welding of two components.
Mass flow meter	A device that measures the mass flow rate of a fluid or gas travelling through a tube.
Movement analysis	The analysis of operator or machinery movements in an effort to eliminate wastefulness, resulting from using unnecessary, ill directed and inefficient motion.
Necessary work	Activities that do not add value to the product or service but are necessary to complete the product.

Non-value adding work	Work that consumes resources but does not add value to the product or service.
Overall equipment effectiveness	A measure of how well a manufacturing operation is utilized compared to its full potential, during the periods when it is scheduled to run/produce.
Poke-yoke	Mistake-proofing methods aimed at designing fail-safe systems that minimise human error.
Production line efficiency	A measure that describes the ratio of the current productivity level to that of the best productivity level
Resistance spot welding	A process where heat from electrical resistance is used with force and time to weld metallic materials.
Shielding gas	Gases that are used in several welding processes, most notably gas metal arc welding to protect the weld area from oxygen and water vapour.
Single minute exchange of die	A system for dramatically reducing the time it takes to complete equipment changeovers.
Standardized work	The safest, easiest and most efficient way to perform a task. The goals are in pursuit of high productivity through activities that are not difficult but are efficient to eliminate inventory and wastes.
Super Lean tools	A set of specific tools that have the greatest effect in the reduction of the seven wastes.
System buffer	Inventory that is used in manufacturing to adjust for variations in the production process and ensure smooth production.

System dynamic modelling	The study and analysis of production line systems using computer simulation modelling techniques.
Tachometer	A tool that is used for the measurement of speed or distance.
Takt	A manufacturing term to describe the required product assembly duration that is needed to match the customer demand.
Total quality management	The continual process of detecting and reducing, or eliminating errors in manufacturing.
Toyota Production System	An integrated socio-technical system developed by Toyota that comprises its management philosophy and practices.
UPR X BKT	A weld procedure within the Auxiliary Cross member manufacturing process. This process entails the assembly and welding of sub-components that are required for the Auxiliary Cross member.
UPR X HOOK	A weld procedure within the Auxiliary Cross member manufacturing process. This process entails the assembly and welding of sub-components that are required for the Auxiliary Cross member.
UPR X LWR	A weld procedure within the Auxiliary Cross member manufacturing process. This process entails the assembly and welding of sub-

	components that are required for the Auxiliary Cross member.
Value adding work	Work that transforms the product from raw material into finished goods.
Worker movement chart	A chart that illustrates the movement of the operator in relation to each element of his cyclic work.

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Chapter 1

Introduction

1.1. Background to the Study

A common factor for industrial production is energy, and the level of energy consumed was typically used to measure the progress and economic development of countries. It was thus a given that as industrialization and the population thrived, there was an increased reliance on energy (Pardo Martinez 2010).

It can therefore be deduced that energy was at the heart of development and was a vital force that powered business, manufacturing, the transporting of goods and the delivering of services(Keneilwe Ratshomo 2019).

The global energy consumption for the industrial sector was greater than any other end use sector, with approximately 54% of the world's total delivered energy(Conti *et al.* 2016). Within a South African context, the industrial sector followed a similar trend, consuming a total of 52% of energy, and again being the highest among other energy demanding sectors (Keneilwe Ratshomo 2019).

However, as the industrial sector expanded and made efforts to gain a competitive advantage, there was a growing concern regarding energy consumption and the ecological burden related to energy usage. Over the past few years energy efficiency within the manufacturing sector has become a priority. The use of manufacturing operations was responsible for significant Green House Gas (GHG) emissions and thus climate change (Kivyiro and Arminen 2014).

The South African energy supply has been dominated by coal, which has constituted 69% of the primary energy supply(Keneilwe Ratshomo 2019). It can therefore be concluded that the level of GHG emissions resulting from manufacturing operations have a strong correlation with the level of energy efficiency. The severity of the environmental situation is forcing organizations to not only focus on operational excellence, but also to rethink how the operations can be more environmentally sustainable.

1.2. Manufacturing Sector and the Environment

The manufacturing sector in South Africa is the cornerstone of growth as it enables job creation, broadens supply chains and advances technology. Agro-processing, automotive manufacturing, chemical manufacturing, information and communication technology, electronics, metals, textiles, clothing and footwear manufacturing dominate the sector.

Within this manufacturing basket, automotive manufacturing is the largest Gross Domestic Profit (GDP) contributor, with a large influence from Original Equipment Manufacturers (OEMs). These OEMs allow for the sourcing of components, assembly of vehicles and distribution to both local and export markets. In addition, the South African automotive industry is the largest on the African continent and forms a fundamental part of the South African economy(Davies *et al.* 2019).

Together with its dominance in the South African economy, the contribution of the automotive industry to the total national environmental impact generated from high production and energy-consuming activities has been significant (Kehbila, Ertel and Brent 2009).

The total energy consumed during the life cycle of a car can be summarized into four main stages that include raw material processing, car manufacturing, car use and recycling. These are highlighted further below:

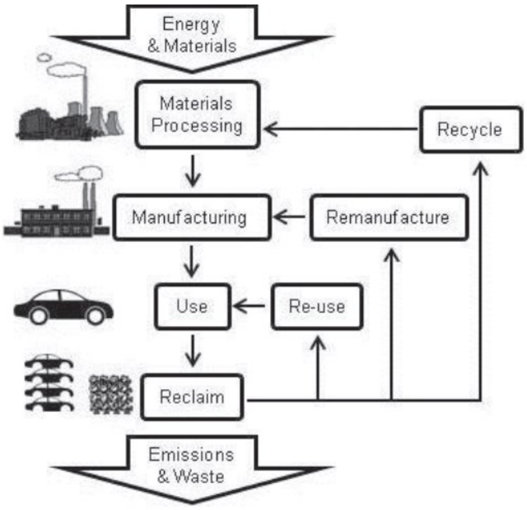


Figure 1: Car life cycle (Fysikopoulos et al. 2012)

The car manufacturing stage was said to consume up to $700\,kWh$ per vehicle produced(Fysikopoulos *et al.* 2012). Countries within the Organization for Economy Corporation and Development (OECD) that include Japan, Germany and the United States emit approximately $303\ kgC0_2$ per vehicle. In a South African context, considering that the majority of the energy is coal powered, this amounts to approximately $668\ kgC0_2$which is more than double in emissions per vehicle produced.

Comparing the South African automotive industry to that in other developing economies, there is a noticeable shift in the paradigms, where sustainable operations are starting to accompany the customary key performance indicators of productivity, cost competitiveness and quality.

An example to note was the Malaysian automotive industry, which had been identified as one of the main causes of pollution in the country. The counter approach of the industry had been to introduce policies and incentives that allowed for effective and efficient adoption of sustainable operations(Ng and Hamid 2017).

Similarly, the Brazilian automotive industry experienced rapid growth and generated great value to the country's economy. Globalisation allowed for the extensive implementation of Lean Manufacturing principles that were instilled as a culture. Lean thinking provoked the concepts of sustainable manufacturing and green operations to increase environmental performance(Vanalle *et al.* 2017).

Just as the Malaysian and Brazilian automotive industries have seen substantial growth, South Africa has also experienced significant development. The industry expansions have, however, almost instantaneously triggered energy demands that are becoming exponentially higher than similar countries, leaving behind the environmental burden of increased GHG emissions.

1.3. Problem Statement

Thus far, industry has heavily relied on the Lean Manufacturing paradigm and has gained the contemporary benefits of profitability, flexibility, increased efficiency and customer satisfaction(Garza-Reyes 2015). The success of Lean Manufacturing lies in its core strategy that is to identify and eliminate non-value adding activities known as wastes. Adapting this methodology through the Toyota Production System (TPS), Lean has proved to be a world-renowned enhancer of competitiveness.

According to Chiarini (2014), Lean focused on seven key wastes that included overproduction, excessive inventory, transportation, unnecessary motion, defects, waiting and over processing. By avoiding these wastes, an organization could lower production costs and lead-time to customers. Several Lean tools to curb and eliminate the wastes could be used during manufacturing activity. The most critical tools included Value Stream Mapping (VSM) to identify wastes within a production or supply chain, Total Productive Maintenance (TPM) to reduce machine failure, and Standardized Work to ensure correct and consistent operational sequence.

Some authors and practitioners in the field have claimed that by reducing these specific wastes using Lean tools, a reduction in greenhouse gas in the form of emissions into the air, soil and water would occur. Similarly, an increase in the efficiency of electricity consumption would be noticed. At this point it is, however, difficult to understand the exact kind of correlation that exists between Lean tools and the effect on environmental impacts, and whether these correlations can be measured quantitatively.

1.4. Hypothesis

H_1 : If Lean techniques are applied to a production line to reduce the seven wastes, this will simultaneously result in a reduction of GHG emissions.

1.5. Delimitations

This research work took place in KwaZulu-Natal, a province in South Africa that occupies the south-eastern part of the country. The scope of the study was limited to one company and was concerned with the manufacturing of automobiles. The research was case study based and entailed the observation of a weld process production line within Toyota South Africa Motors (TSAM). The specific production line was the International Multi-purpose Vehicle (IMV) Chassis Cross Member line based in the Toyota Chassis Plant (TCP) and was selected for the following reasons:

- As TSAM is an affiliate to The Toyota Motor Corporation, there is a strong presence and commitment to Lean Production. Studying and implementing lean principles would be much easier due to this, as the framework had been developed and instilled within the company and its people.
- The plant is committed to the sustainable operations strategy. The plant-wide 2050 goal for TSAM is to strive towards a zero emissions plant. With the drive to achieve this goal, the company and the people have a much greater sense of environmental awareness.
- The plant relies heavily on weld processes. These processes share similar characteristics across the plant and the knowledge gained from this study could be applied to the remainder of the weld processes.

The area of focus within the IMV Chassis Cross Member production line was the Auxiliary Cross sub-assembly, as it was the most frequently used component between all model derivatives. The production operation for this line consisted of a two-shift system and utilizes four operators per shift.

The study was quantitatively based and made use of field experiments. The two-shift system was favoured as it made it easier to distinguish between a control and an experimental group. The independent variables, which were the lean techniques applied to the seven wastes, and the dependent variables, the GHG emissions, were measured.

The three key attributes that were identified made up the majority of the GHGs emitted. These included compressed air, weld shield gas and electricity, which were essential services required for the line to function. In addition, a segment of solid waste in the form of weld wire packaging was evaluated, as the weld wire was the principal consumable.

1.6. Aims and objectives of the study

The aim of this research was to investigate the correlation between Lean tools and GHG emission within an automotive manufacturing organization. The study identified the present state of emissions generation within the Auxiliary Cross sub-assembly production line and applied Lean techniques derived from the literature review and body of knowledge. Based on the application, the advantages and disadvantages of each technique were evaluated.

The objectives of the study were to:

- Develop a framework to improve current environmental performance through Lean Manufacturing.
- Investigate and measure the current GHG emissions rates of the weld production rate.
- Apply Lean tools to determine whether they can reduce or mitigate GHG emissions.

1.7. Research Methodology

The literature review emphasizes the correlation between the Lean and Green paradigms and draws attention to the fact that GHG emissions are more likely to occur during the seven wastes of Lean Manufacturing. The initial step of the methodology follows this concept of linking Lean and Green wastes and develops a conceptual framework that illustrates three key Lean tools that have a significant effect on the seven Lean wastes and ultimately, the GHG emissions.

By means of the conceptual framework, the research design followed the path of a causal type study with the purpose being to test the cause and effect theories through field type experiments. For the field type experiment setting, the production process of the Auxiliary Cross sub-assembly line was utilized to apply the theories and analyse the outcomes.

The management structure of the TCP process consisted of day- and night-shift operations, which allowed for easy selection of control and experimental groups. In terms of sample size for experimental data collection, a sample size of 26 production cycles was selected for each experiment. The sample size was a joint agreement with production management to avoid any disruptions to the production volume and quality operations, while maintaining the completion target for the study.

The experiment design involved the development of four experiments to test each Lean tool. The first experiment, Preliminary Work, was conducted with the intention of testing the feasibility of the study and determining whether the methodology adopted would meet the objectives of the study. It also provided the opportunity to clearly identify all the major GHG emitters and provide a set of base results to test the effect of each Lean treatment. In addition, the measurement tools were identified, and their capability and viability tested.

The procedures of experiments 2, 3, and 4 are described in detail in chapter 3 following a structured approach to ensure consistency of results obtained and to reduce margins of error.

The final section of the methodology explains the data collection method. The data was collected using specific measuring instruments over the sample size for each GHG emitter. The mean values generated were converted to a common unit of measure to support the analysis and interpretation process.

The independent and dependant variables were clearly established. The data obtained from the experiments were tabulated and graphed accordingly.

1.8. Justification for the study

South Africa finds itself in a unique situation compared to other developing economies. The first, as previously mentioned, is the increase in GHG emissions as the industry expands. The second is the prolonged energy crisis that the country faces. Pollet, Staffell and Adamson (2015) emphasised that chronic under-investment in the electricity sector has led to escalating power processing and capacity shortages during demand periods, leading to demand rationing and load shedding.

The focus of this study deals with efforts to reduce GHG emissions through Lean techniques and creating sustainable operations for the future of manufacturing. Additionally, in the unique case of South Africa, it creates the opportunity to reduce energy consumption and support the main energy provider.

The quantitative data obtained from the experiments will support the rationalising of relationships between Lean techniques and how they affect emissions. The success of the study will not only contribute to the current body of knowledge, but also allow practitioners and scholars to use the data obtained as a foundation for further studies. Small to Medium Enterprises could also benefit from the study by understanding the additional advantages of Lean Manufacturing.

Although the energy crisis in South Africa is not a focus item of this study, the aim of reducing GHG emissions and energy demands provides a starting point to explore new ways to relieve the energy crisis in the country and lessen the social and economic consequences.

1.9. Research Outputs

During this research, the following are the outputs:

- *Keshav Ramsunder and Oludolapo A. Olanrewaju.* Energy Analysis via Value Stream Mapping: A case study of an Automotive Weld Plant. Orion: Journal of the Operations Research of South Africa. (Submitted)

1.10. Research Layout

The dissertation is divided into five chapters. A brief description of the content of each chapter follows:

- Chapter 1
  The introductory chapter provides an overview of the global environmental challenges facing the manufacturing industry. The South African automotive industry and how it is a key role player in the country's economy is discussed. The paradigm of Lean Manufacturing is discussed along with the rationale behind the study, the problem statement, and the aims and objectives.
- Chapter 2
  The literature review provides an extensive assessment of existing literature regarding the Lean and Green paradigm. The chapter begins with the description of Lean tools and how they have moulded the industry. Alternative management frameworks for cleaner operations along with Green Manufacturing are described and critiqued. The chapter finally explores the combination of Lean and Green to support a sustainable manufacturing industry.
- Chapter 3
  The methodology chapter incorporates the theoretical and conceptual frameworks derived from the literature review to develop the foundation of the research design.

It provides the study setting, the control groups and sample size, followed by the experiment design and data collection methods.

- Chapter 4

  The results and discussion reveal the findings and analysis of the study. The results are displayed using a Value Stream Map to provide a holistic view of the findings and their effect.

- Chapter 5

  The conclusion and recommendations form the content of the final chapter and provide further discussion of the data gathered and the limitations of the study. In addition, a detailed discussion of recommendations emanating from the current study and further investigation is provided.

1.11. Summary

This chapter has outlined the contemporary issues that the manufacturing industry is facing and has introduced the quest to create more sustainable operations. The chapter also introduced the design motives and methodology implemented to carry out the research. The next chapter reviews the literature and existing frameworks developed thus far.

Chapter 2

Literature Review

2.1 Introduction

In keeping with the objective of the study, which was to investigate the impact of Lean Manufacturing on the environment and GHG emissions, the Lean and Green paradigms were first reviewed as separate entities. This chapter consists of three sections describing how existing literature guided the investigation.

Section 2.1 consists of reviews of Lean Manufacturing and outlines how they have affected and moulded the manufacturing industry of today. Section 2.2 highlights current Environmental Management Systems and how they fit into industry, as well as critical factors for success. Within this section, alternate concepts, which include Green Manufacturing and Eco-efficiency, have been reviewed to provide a broader background to understanding the related strengths and weaknesses of stand-alone systems.

Finally, Section 2.3 is divided into two areas of review. The first area investigates the concept of Lean positively influencing the environment. The theoretical benefits outlined provide a wider spectrum of the expected outcomes of Lean Manufacturing and its environmental impact. The second area highlights empirical studies carried out and discusses the strengths and uniqueness of the paradigm.

2.2 Lean Manufacturing today

Over the past few decades, Lean Manufacturing has been viewed as one of the most popular strategies for cost and waste reduction. Developed for the Toyota Production System, Lean Manufacturing is a popular instrument that is widely applied in the manufacturing and service sectors. Increasing customer value and minimizing non-value activities are the core concepts. Many firms thus practise Lean Manufacturing to reap the benefits of enhanced quality and productivity.

Lean has offered organizations an array of tools that reduce and eliminate waste from business processes. Practitioners traditionally focused on eliminating, or reducing, the seven wastes to achieve this. These included overproduction, excessive inventory, transportation, unnecessary motion, defects, waiting and over processing (Sundar, Balaji and Kumar 2014).Some of the Lean methods used to identify and eliminate these wastes within a process were Value Stream Mapping (VSM), Total Productive Maintenance (TPM), Standardized Work, and Continuous Improvement. These were seen as the most essential tools for leaning a process out (Belekoukias, Garza-Reyes and Kumar 2014).

VSM was a visually based method which illustrated, identified and measured wastes that resulted from inefficiencies in equipment, information, time and material during the production process (Arunagiri and Gnanavelbabu 2014). TPM supported the prediction, prevention and improvement of corrective measures to achieve efficient production equipment. TPM relied on tools such as Overall Equipment Effectiveness, planned maintenance and autonomous maintenance (Konecny and Thun 2011).Standardized Work was a detailed visual document that was developed for cases where a series of pre-defined steps were required to be followed. These detailed steps represented the best practices for workers to follow and formed the foundation for continuous improvements to take place (Ingaldi and Jagusiak-Kocik 2014).Continuous improvement was the removal of waste through incremental improvement of operations and served to sustain Lean once it was embedded into the culture of the organization (Rocha-Lona, Garza-Reyes and Kumar 2013).

Many manufacturers have investigated and implemented these Lean methods as part of their efforts to gain competitiveness and flexibility in today's volatile environment. The development of Toyota Production Systems has seen the automotive sector become a pioneer of Lean Manufacturing with economic growth year on year(Staeblein and Aoki 2015).The research by Al-Saleh (2011) improved operations at a Motor Vehicle Periodic Inspection Station. Utilizing an array of Lean tools and simulation packages, production capacity improved by 178%.

Rahani and Al-Ashraf (2012) analysed the production flow of an automotive component manufacturer using Lean production techniques. The application of VSM identified excessive wastes in the form of inventory and rejects. With the implementation of Standardized Work, the authors were able to reduce inventory and reject rates while improving productivity. Similarly, Nguyen and Do (2016) utilized VSM to identify wasteful activities within an electronics assembly line. The study showed a 40% reduction in labour and further reductions in lead-time from 7.5 days to 3.5 days. Additionally, a floor space saving of 30% was realised.

Rosa, Silva, and Ferreira (2017) improved competitiveness and reduced costs by optimizing the assembly line process of steel wire ropes used to control the elevation of car door windows. Using Lean methods, specifically VSM, TPM and Standard Work sequence, led to the elimination of wasteful activities and resulted in a 41% increase in productivity .

Although Lean Manufacturing was originally developed for the automotive industry, many alternative industries have found that the application of these principles could yield dramatic efficiency improvements. Within the heating, ventilation and air conditioning industry, Das, Venkatadri and Pandey (2014) realised a 76% improvement in the productivity of air conditioning coils. The key Lean tools such as VSM, continuous improvement and TPM improved manufacturing capacity from 121 units to 214 units per shift. Similarly, Rohani and Zahraee (2015) found that by performing VSM studies within the paint industry, the implementation of Lean Manufacturing techniques (5s, Kaizen, Kanban) decreased production lead time from 8 days to 6.5 days and the non-value added time was reduced from 68 minutes to 37 minutes.

Duran, Cetindere and Aksu (2015) improved productivity within a glass manufacturing company using Lean Manufacturing techniques. By using the principles of Standardized Work, the work content was analysed and non-value adding activities eliminated through continuous improvement. The implementation of these techniques saw a gain of 53% in productivity. More recently,Garre *et al.* (2017) applied Lean principles to the aeromotive industry in their efforts to increase productivity and quality. Implementation of 5s and layout configuration saw reductions in inventory and smoother flowing operations. The introduction of standardized work methods led to an overall increase in productivity and a decrease in operating cycle time.

Lean Manufacturing has become the most influential paradigm in industry. The authors mentioned above have supported the fact that it is an effective method to improve competitiveness and agility. Climate change, scarce natural resources and environmental deterioration are, however, some of the major challenges that humankind currently faces. As a major contributor to these challenges, manufacturing organizations are being persuaded to develop cleaner operations.

2.3 Environmental Management Systems and Green Manufacturing

Many authors have investigated new management systems, frameworks and strategies to increase environmental performance. These include management systems such as ISO 14001, Life Cycle Analysis and strategies that include waste management and the 3R hierarchy (Reduction, Reuse and Recovery).The concept of the ISO 14001 Environmental Management System was introduced to guide companies in the evaluation of key drivers of and barriers to environmental improvement. However, the system still required integration into an existing production system in order to function. Further difficulties included commitment from human resources, calculating outcomes and environmental information(Martín-Peña, Díaz-Garrido and Sánchez-López 2014).

According to Singh, Brueckner and Padhy (2015), ISO 14001 was utilized for waste minimization activities in India. The certification supported the reduction of waste; however, it was found only to be effective working concurrently with an existing production management system. Similarly, Souza and Alves (2018), in the integration of environmental management and Lean management, supported organizations to improve corporate sustainability in a structured manner. The research introduced an integrated management system that considered the difficulties of organizations performing sustainability improvement activities to avoid loss of organizational efficiency due to waste.

The Life Cycle Assessment could achieve significant benefits predicting the life cycle impacts and in turn find new solutions to reduce environmental impacts. Industry could use this assessment to analyse and understand their greatest environmental impacts and directly reduce the negative effects. It was, however, complex, expensive and time consuming to integrate it into an existing production framework as it required data at every stage of the life cycle(Sonego, Echeveste and Debarba 2018). Life Cycle Assessment was part of the ISO 14001 Environmental Management System which provided a guideline on how to carry out the assessment. However, Zackrisson, Avellán and Orlenius (2010) emphasised that these were only guidelines to assess the environmental impacts associated with all stages of a product's life.

Waste management strategies such as the 3R hierarchy consisted of different measures to minimize the volume of discarded work materials (azimi Jibril *et al.* 2012). Schroeder and Robinson (2010) agreed and added that the 3R hierarchy was an internationally accepted policy for waste management focused on waste reduction at the source. However, Fercoq, Lamouri and Carbone (2016) argued that the 3R hierarchy could only be regarded as a reference method for operating a waste management progress plan. The authors further stressed that although a large number of studies had developed optimization methods, there was no quantitative study that had demonstrated the impact of 3R or any other environmental tool highlighting the minimization of solid waste in the manufacturing industry.

The review of Environmental Management Systems highlighted that it specified a framework for an organization to monitor and control their environmental impacts. At the same time, the literature also suggested that these structured processes should be integrated and supported by an existing manufacturing system. Environmental paradigms were treated with a micro-perspective; however, in addition to the Environmental Management Systems, further conceptual frameworks for waste minimization have been developed.

Nunes and Bennett (2010) focused on investigating and benchmarking Green operations initiatives in the automotive industry. The environmental reports of the Toyota Motor Corporation, the Volkswagen Group and General Motors highlighted a pattern of integration of environmental management systems into an existing manufacturing system to gain maximum benefit. Deif (2011) presented a system model for a new Green concept. The purpose included the development of a high-level framework to understand Green Manufacturing. The framework included the planning of activities required to assess the current Green level of the manufacturing system, to move from a less Green to a more eco-efficient manufacturing method and finally, to sustain the achieved improvements.

Sezen and Çankaya (2013) examined the influence of Green Manufacturing and eco-innovation on corporate sustainability performance. Through the use of a questionnaire-based survey, it was found that Green Manufacturing applications had a significant positive impact on environmental performance. Patel, Bhole and Chaudhari (2014) focused on Green design for the environment of a Green Manufacturing system, energy consumption and the development of products with less wastage. Their work supported the use of Green Manufacturing to form recyclable and sustainable products and create awareness for the mass production of goods. In doing this, it was suggested that the waste reduction methodology of Green Manufacturing could increase sustainability and reduce the costs of the product.

It is evident that environmental concerns have a vital role to play in strategic manufacturing decisions, hence the study of environmental management systems and green conceptual frameworks. The literature reviewed thus far has demonstrated the use of environmental management systems and Green initiatives along with their respective benefits. It has also been emphasised that environmental management systems posed more of a catalyst effect to an existing manufacturing system and the assimilation of these concepts could yield the benefits of reduced environmental impacts and improved corporate image. However, these environmental improvements have not been clearly quantified and the authors have not recommended the implementation of Lean Manufacturing or its tools and principles.

2.4 Lean and the effect on the environment

By contrast, some papers have explored the relationship between the concepts of Lean Manufacturing and Environmental, or Green Management. Garza-Reyes *et al.* (2018) suggested that the starting point for the development of better strategies to support environmental sustainability was to explore the opportunities that were in use as best practices. Lean Manufacturing might provide environmental benefits and could be adapted to meet sustainability requirements. Various authors have provided conceptual models on the effect of Lean tools on the environment.

Hines (2009) initially proposed the categorization of eight Green Manufacturing wastes. These included greenhouse gases, eutrophication, excessive resource usage, excessive power usage, pollution, excessive water usage, and poor health and safety. This categorization was inspired by Lean Manufacturing and provided the link to the eradication of manufacturing wastes. Using this proposal, Verrier *et al*. (2014) went further and provided a clear correlation between Lean and Green wastes. The authors found that:

a) Excessive power usage was critical as it was affected by almost every Lean waste.
b) Excessive resource usage was affected by overproduction and defects. Secondary causes could be transportation, inventory, unnecessary processing and waiting.
c) Depending on the process type, resource and power usage could relate to excessive water usage and possibly cause injury to people or damage the environment. These wastes were followed by solid waste, direct emissions, and poor health and safety.

Mollenkopf *et al.* (2010) found that companies that practised Lean Manufacturing were more likely to accept environmental thinking and systems as they already had an organizational structure that supported waste reduction. Further understanding the synergies between lean and green allowed for more effective decision-making, while staying competitive in a complex supply chain system. Vinodh, Arvind and Somanaathan (2011) suggested that environmental benefits could be triggered by the implementation of Lean Manufacturing. The evaluation consisted of environmental impacts and the quantification of sustainable gains when Lean principles were applied. Furthermore, a systematic strategy using Lean principles to obtain sustainability objectives was applied.

Dües, Tan and Lim (2013) proposed that Lean practices could act as a medium for the greening of supply chain operations and enhance the understanding of a Lean and Green relationship. Their insights suggested that Lean practices were synergistic for Green and that the Lean framework was a vehicle to support the greening of the process. Johansson and Sundin (2014) compared Lean and Green methodologies through a literature review study. Several overlaps were highlighted between the concepts; for example, the race for competitive advantage through a more efficient and effective process was a driver for both Lean and Green Manufacturing. The study concluded that Lean and Green were of the same currency as they shared a number of similarities that indicated a synergistic relationship.

Based on a case study approach, Galeazzo, Furlan and Vinelli (2014) described how the Lean and Green concept could be integrated to achieve maximum synergy and improve both operational and environmental performance. Three significant findings were noted during the study. Firstly, managers should simultaneously implement Lean and Green practices.

Secondly, manufacturing operations and Green practices should be integrated to maximize performance. Finally, resources and capabilities of different departments within the organization should be combined to align in achieving maximum environmental and operational performance.

Garza-Reyes (2015) advocated this finding and illustrated that the Lean approach to reducing waste provided an atmosphere that could foster Green initiatives. These initiatives included reducing GHG impacts by minimizing energy and natural resource consumption. Maruthi and Rashmi (2015) further evaluated the vital aspects of Green Manufacturing and how Lean Manufacturing could gain sufficient environmental benefits through waste reduction techniques. The research went on to describe that the elimination of waste represented the ultimate solution to pollution problems that threatened the eco-system.

Carvalho, Duarte and Machado (2011) and Garza-Reyes *et al.* (2014) drew parallel conclusions that the objective of Lean Manufacturing, which was waste reduction, aligned itself with good environmental practices. Tackling the seven wastes of Lean Manufacturing could lead to environmental benefits. For example, reducing excessive transport could minimize operation costs and in addition reduce unnecessary GHG emissions and consumption of natural resources.

Abreu, Alves and Moreira (2017) stipulated that the saving gained by Lean initiatives resulted in environmental benefits. Their work involved the completion of a comparative analysis of the existing models and found that the fundamental objective of the Lean and Green paradigm was to:

a) Improve productivity while reducing environmental impacts.
b) Attain sustainability and greener industrial activity through integration of the concepts.

The study of Caldera, Desha, and Dawes (2017)undertook a systematic literature review to investigate whether Lean and Green practices could lead to sustainable business operations. Through their literature the authors developed a matrix that identified opportunities to implement Lean and Green thinking within five work streams. These included waste, energy, emissions, water and chemical management. The development of the matrix provided insights into a replicable system that could be used across industries to reduce waste and increase material efficiency.

Cai (2019) correlated the relationship between Lean and Green through the proposal of a new concept called Lean Energy Saving and Emissions Reduction (LESER). The concept built on its predecessor, Energy Saving and Emissions Reduction (ESER) and used Lean principles to reduce energy consumption and decrease industrial waste emissions. The paper drew on the methodology from Lean thinking and emphasised a Lean approach to Green thinking.

The conceptual reviews presented here have shown the potential benefits of Lean tools and environment emission reduction. They have also suggested that Lean Manufacturing could improve environmental performance and provide the foundation for the paradigm. With this in mind, a few scholars have focused on empirical investigations of this paradigm. Yang, Hong, and Modi (2011) explored the relationships between Lean Manufacturing, environmental management and business outcomes. The relationships were empirically tested through data gathered from a large sample of 304 manufacturing firms. The findings suggested that environmental management activities applied in isolation might lead to negative impacts; however, concurrent application of Lean has led to a positive influence across manufacturing processes.

Bandehnezhad, Zailani and Fernando (2012) investigated the effect of Lean practices on environmental performance within different functional sectors of manufacturing firms. The quantitative survey illustrated that Lean practices involved with area, process and equipment, human resources, product design and customer satisfaction had a positive impact on environmental performance. A study conducted by Hajmohammad *et al.* (2013) involved the functions of Lean and supply chain management with respect to improving the organization's environmental performance. The outcomes indicated that the knowledge gained when implementing Lean principles was beneficial to environmental practices and further enhanced those practices.

Garza-Reyes *et al.* (2018) used common Lean tools such as Just in Time, Total Productive Maintenance, autonomation, Value Stream Mapping and Kaizen to evaluate the impact of manufacturing on environmental performance. The results indicated that Total Productive Maintenance could improve equipment performance and reduce material utilization. Just in

Time improved quality and reduced production rework. Kaizen aligned itself to academic literature and positively affected the environment. However, by contrast, no significant environmental improvements were observed by the implementation of Value Stream Mapping and autonomation.

Gupta, Narayanamurthy and Acharya (2018) utilized Lean principles along with System Dynamic modelling to assess environmental wastes within a radial tyre manufacturing environment. Through various scenario analyses, the model depicted scrap and rework produced in the production process as contributing to increased pollutants of the environment. Additionally, excessive inventory reduced the greenness level of the firm.

Chiarini (2014) highlighted the environmental impact of Value Stream Mapping, Total Productive Maintenance, 5s, Single Minute Exchange of Die (SMED) and Cellular Manufacturing within the European motorcycle industry. The implementation of these Lean tools showed that Value Stream Mapping could identify the environmental impacts of production processes, 5s improved waste management, and Total Productive Maintenance improved machine life cycle and reduced non-optimized machine functioning. Finally, Cellular Manufacturing reduced electricity consumption. In contrast, the implementation of SMED had no considerable effect on environmental impacts. However, the recent work of Júnior *et al.* (2018) focused solely on SMED activities and the effect on the Carbon footprint and eco-efficiency. Five different scenarios were organized by varying machine tools, workers and work pieces. The SMED tool was applied and reduced idle time by 88%. The carbon footprint showed a similar reduction of 81% while the eco-efficiency improved by 3%. In achieving such results, the authors emphasized the use of standardization of work methods and simple improvement activities to reduce idle time and increase productive time.

2.5 Summary

This chapter has demonstrated the key focus areas of Lean and Green Manufacturing. The paradigms were critiqued based on the available literature and as stand-alone systems. Thereafter, the impacts of Lean Manufacturing on the environment were assessed both conceptually and empirically. The literature justified that the implementation of Lean has had positive effects and synergies on the environmental aspects of a production process.

As was the case with the empirical studies reviewed, this study intended to investigate the effect of Lean techniques on environmental performance within the South African automotive Industry. The study made use of the essential tools of VSM and TPM to complement the previous research and expanded on the current body of knowledge of the Lean and Green paradigm. In addition, to further explore the effect of Lean tools on the environment, Standardized Work was also implemented in an effort to reduce the knowledge gap.

Chapter 3

Research Design and Methodology

3.1 Introduction

In this chapter, the selection of an appropriate research design along with the field experiment setting will be discussed. This chapter explains the theoretical and conceptual frameworks that guided the entire process within this research. A description of the data collection instruments will be examined followed by the population and sample size.

3.2 Research Strategy

As mentioned earlier, the aim of the study was to investigate the correlation between Lean tools and GHG emissions. The investigation strongly focused on the application of a set of lean tools within the manufacturing process of the (IMV) Chassis and the effect on the generation of GHG emissions. The objective was to develop a framework to investigate GHG emissions during production operations and determine whether Lean tools could reduce or mitigate these emissions. The study took place in the Chassis Weld Plant of Toyota South Africa Motors (TSAM) as a high sense of Lean thinking and environmental consciousness already existed within the plant.

The environmental impacts were measured and observed via a unit measure of $kgC0_2$. The literature review has highlighted VSM, TPM and Standardized Work as the most essential tools in leaning a process out. Hence, for the purpose of this study they were taken into consideration for deeper investigation. Furthermore, these tools were selected as they form part of the fundamental principles of Lean Manufacturing and have been proved to support a sound business model(Elbert 2013). A comparison of the ‘before’ and ‘after’ results was carried out to support the quantifiable correlation between Lean tools and GHG emissions.

3.3 Theoretical Framework

The research project centred on the association of the Lean and Green paradigm with specific emphasis on both manufacturing and environmental wastes. The Lean and Green themes associated with manufacturing processes were addressed by several recent papers such as those by (Pampanelli, Found and Bernardes 2014; Kurdve *et al.* 2015). Lean management has had a positive impact on environmental management which in turn showed a positive impact on operation performance (Jabbour *et al.* 2013). Simpson and Samson (2010) illustrated how the use of enhanced manufacturing techniques such as Lean, JIT and Total Quality Management had a positive effect on environmental performance (Simpson and Samson 2010).

These theoretical findings, together with the literature review, have illustrated positive links between the Lean and Green paradigms as well as supporting the aim and objectives of this study. However, it was not clear what kind of relationships existed between specific Lean tools and their effect on environmental impacts and whether their relationships could be measured quantitatively. Hence, from the above literature, a supporting theory as shown below could be formulated:

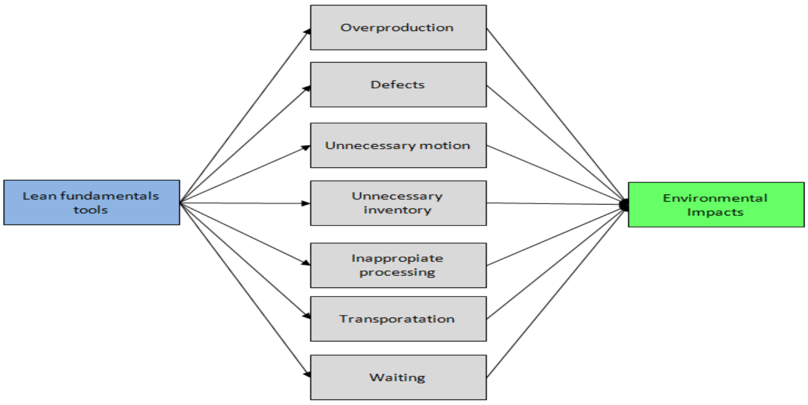


Figure 2: Lean and Green links through seven wastes (Author's concept)

In conjunction with the literature review, the above figure illustrates the theoretical framework upon which the study was based. By developing the links between the seven wastes and the environmental impacts, reducing lean wastes would result in a reduction of environmental impacts.

3.4 Conceptual Framework

The literature review emphasized the correlation between the Lean and Green paradigm and further outlined that Green wastes were more likely to occur as a result of Lean wastes. Hence, by clearly identifying the links between the Lean and Green wastes, the Lean tools that had a potentially beneficial influence on Lean wastes would have a similar potentially beneficial influence on Green wastes. This is further illustrated in Figure 3 below:

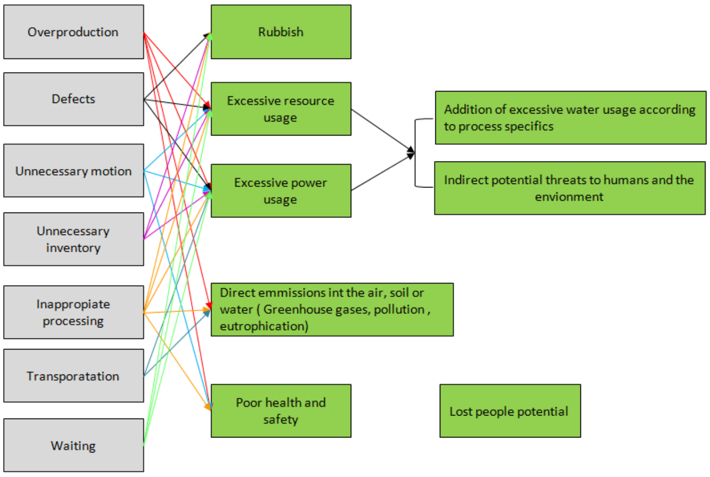


Figure 3: Causal links between Lean and Green wastes (Verrier, Rose and Caillaud 2016)

The Lean wastes had a direct causal effect on each of the Green wastes highlighted (Agency 2007; Hines 2009). Thus, by utilizing the Lean tools to eliminate Lean wastes, corresponding Green wastes could be reduced or mitigated. Lean manufacturing offers several top tools to reduce wastes. The following Figure 4 illustrates the top Lean tools associated with eliminating Lean wastes:

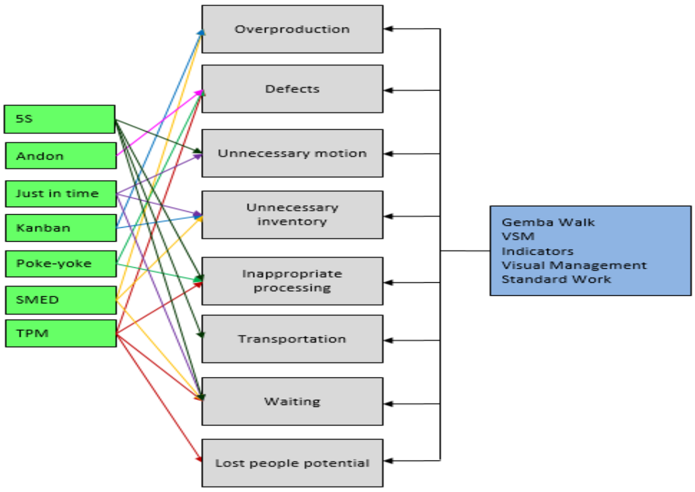


Figure 4: Lean tools and their effect on Lean wastes (Verrier, Rose and Caillaud 2016)

The tools on the left were standard Lean tools while the tools on the right could be considered as Super Lean Tools, as they had a beneficial influence on all Lean wastes and were organizational strategic drivers (Verrier, Rose and Caillaud 2016).Embedded within both the Super and Standard Lean tools, VSM, TPM and Standardized Work are present. In addition to the literature review, additional authors have emphasized the versatility of these techniques.

a) Value Stream Mapping (VSM)

In addition to waste elimination and process efficiency, the conventional VSM could be further extended through to environmental or resource losses. Mapping material usage through different processes was known as Environmental Value Stream Mapping (E-VSM). Specific characteristics of a process such as energy consumption, waste and excess material, along with the activities, time and inventory, could be mapped in E-VSM (Agency 2007). Torres Jr and Gati (2009) also utilized E-VSM and proved it to be an effective way for management to practically address problems to do with production materials.

b) Total Productive Maintenance (TPM)

Total Productive Maintenance has proved to be a maintenance improvement philosophy preventing the failure of an organization (Wakjira and Singh 2012). The goal of a TPM programme was to improve productivity along with increased employee morale and job satisfaction. It was an innovative approach to maintenance that optimized equipment effectiveness, eliminated breakdowns and performed maintenance through day-to-day activities involving the workforce (Singh, Gohil and Desai 2013).

c) Standardized Work

According to Bänziger, Kunz and Wegener (2018), Standardized Work increased productivity and reduced their work index. The repeatability of Standardized Work created a large sequence that reduced errors and wastes probability. Work standardization was required for the planning and positioning of workers, materials, machines, supporting elements and facilities to achieve perfection in the manufacturing environment. Hence, Standardized Work could be said to be a sequential method for defining best practices and supporting Lean implementation (Nallusamy *et al.* 2016). Krichbaum (2008) stated that without Standardized Work being practised, continuous improvement activities were meaningless as a state of constant change could not be improved upon.

TSAM is an affiliate of the Toyota Motor Corporation and therefore practises global manufacturing standards. Over the years, TSAM has been instilling a Lean culture within the organization. The majority of the Lean tools, which include 5s, Andon, Just-In-Time, Kanban and Poke-yoke, have been implemented in the processes and equipment. Therefore, for the scope of this study and aligning with the current body of knowledge, the Lean tools that were applied were VSM, TPM, and Standardized Work.

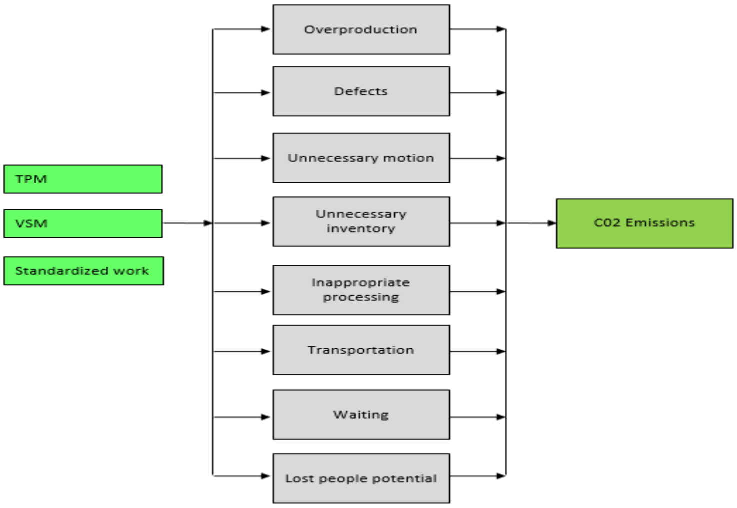


Figure 5: Key lean tools-Conceptual framework (Author's concept)

Hence, the theoretical findings from the literature review and framework study could be summarized and taken under consideration for deeper investigation:

F_1 *-Value Stream Mapping (VSM) could be used as a tool for mapping and identifying environmental impacts in the processes of plant layout.*

F_2*- TPM, when fully implemented and managed, could affect environmental impacts in a positive way.*

F_3 *-Standardized Work, when fully implemented and managed, could affect environmental impacts in a positive way.*

This section highlighted both the theoretical and conceptual frameworks, which set the primary focus of the study. The section to follow details the research design of the project and the options and techniques available for conducting the research.

3.5 Research Design

3.5.1 Nature of the Study

The study at hand involved testing whether Lean tools affected GHG emissions. The unit of the GHG emissions is $kgC0_2$ and can only be measured quantitatively. Hence, the study followed the path of a causal study and focused on the collection and analysis of quantitative data.

Causal studies required variables to be outlined clearly to support a cause and effect theory. These variables included a dependent and independent variable. A dependent variable was one of primary interest and the goal was to understand, describe or predict its variability. The independent variable influenced the dependent variable in either a positive or a negative way. In other words, the variance in the dependent variable was accounted for by the independent variable (Thornhill, Saunders and Lewis 2009).

In the case of this study, GHG would be the dependent variable and the influence of Lean tools would be the independent variable.

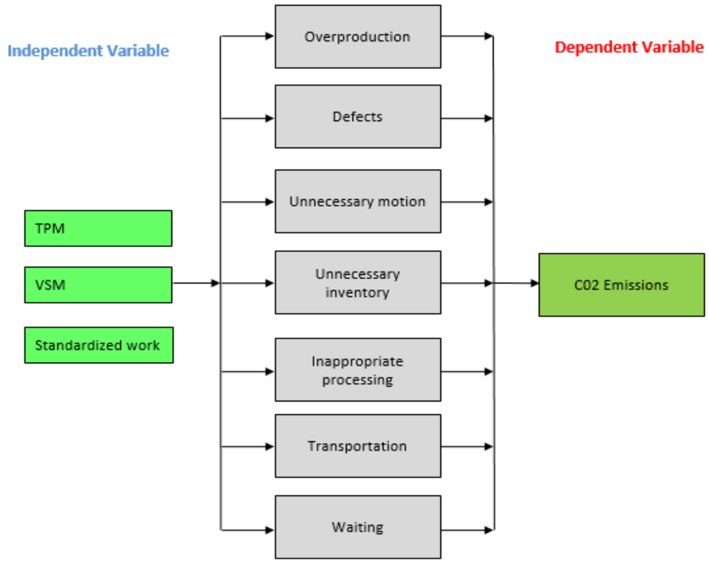


Figure 6: Independent and Dependent Variables (Author's concept)

Experimental designs are often used to establish causal relationships. In the case of TCP, the production line environment would be used as the test field to apply and investigate the effects of the Lean tools. The observations would allow for natural behaviour and illustrate a realistic view of Lean tools. The design of experiments would support the control of the experiment as well as minimize the amount of noise within the variables.

3.6 Design of Experiments

3.6.1 Background

The study took place in TSAM Toyota Chassis Plant. The plant's core function is the assembly and welding of chassis frames for the IMV Hilux. The plant currently has an average output volume of 8958 units per month and utilizes 347 welding operators. The day is broken into a two-shift pattern, a day and a night shift thatlast for 7.5 hours each. These shifts are known as the White shift and the Yellow shift respectively and alternate between day and night on a weekly basis.

A chassis frame consists of side rails and cross members. The frame forms the skeleton structure and holds all the major components of the vehicle together.

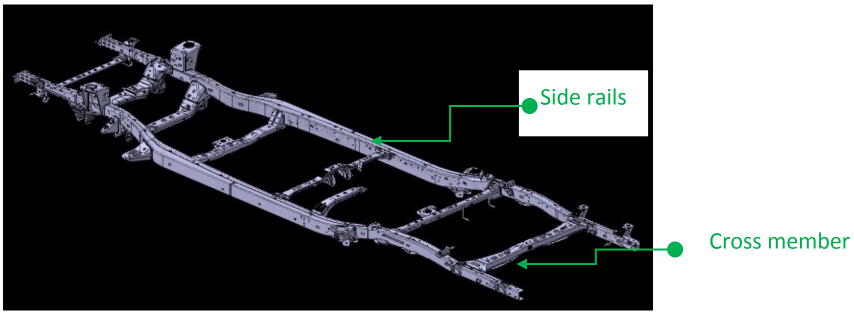


Figure 7: IMV Chassis (Tanaka 2014)

The chassis frames are built on a production line called the Chassis Main Line. The line begins with the assembly of chassis rails that are welded progressively stage by stage using a combination of manual and automated welding techniques. The Gas Metal Arc Welding (GMAW) methodwas exercised within the plant, as it was known for achieving high productivity with good quality results (Ibrahim *et al.* 2012).

On a separatemanufacturing line, the cross members are fabricated and transported to the Chassis Main Line. Using a ’marriage’ fixture, the cross members and rails are assembled and welded together.

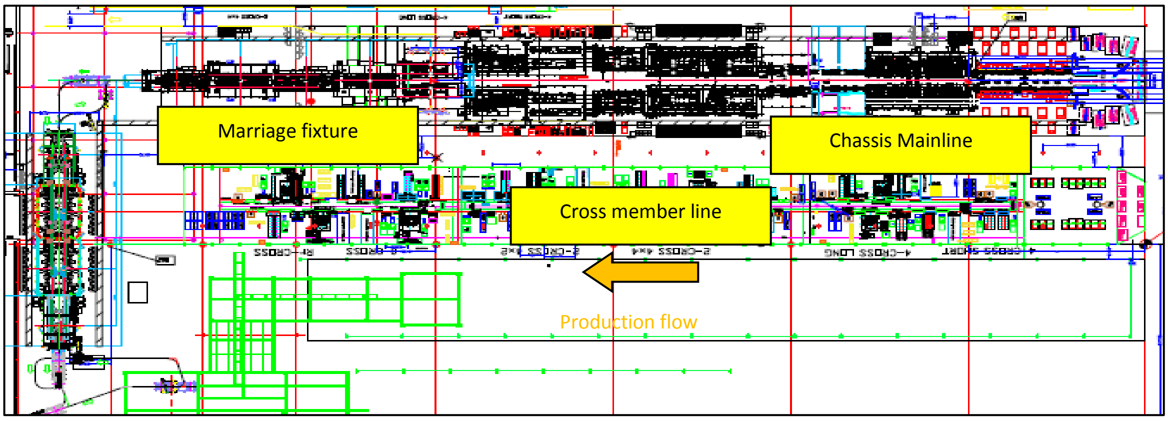


Figure 8: Toyota Chassis Plant Layout (Panter 2014)

The Cross members and Chassis Mainline build 27 different derivatives that support multiple model builds of the Toyota IMV Hilux.The Cross Member Line builds seven types of cross-members to cater for different functional areas of the vehicle and support model variation. These include the suspension, drive train and body mounting specifically.

The production line under focus wasthe Auxiliary Cross production cell. This was selected for the following reasons:

1. Auxiliary Cross is fitted to all chassis models irrespective of derivative.
2. There is a combination of assembly, manual and automated welding in the manufacturing process.
3. From observation, there is a high inventory of finished goods.
4. From observation, there is an overproduction condition.

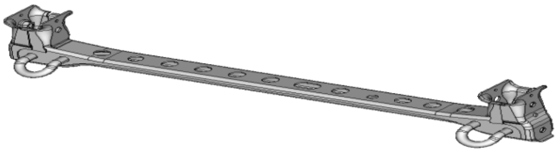


Figure 9: Auxiliary Cross member (Tanaka 2014)

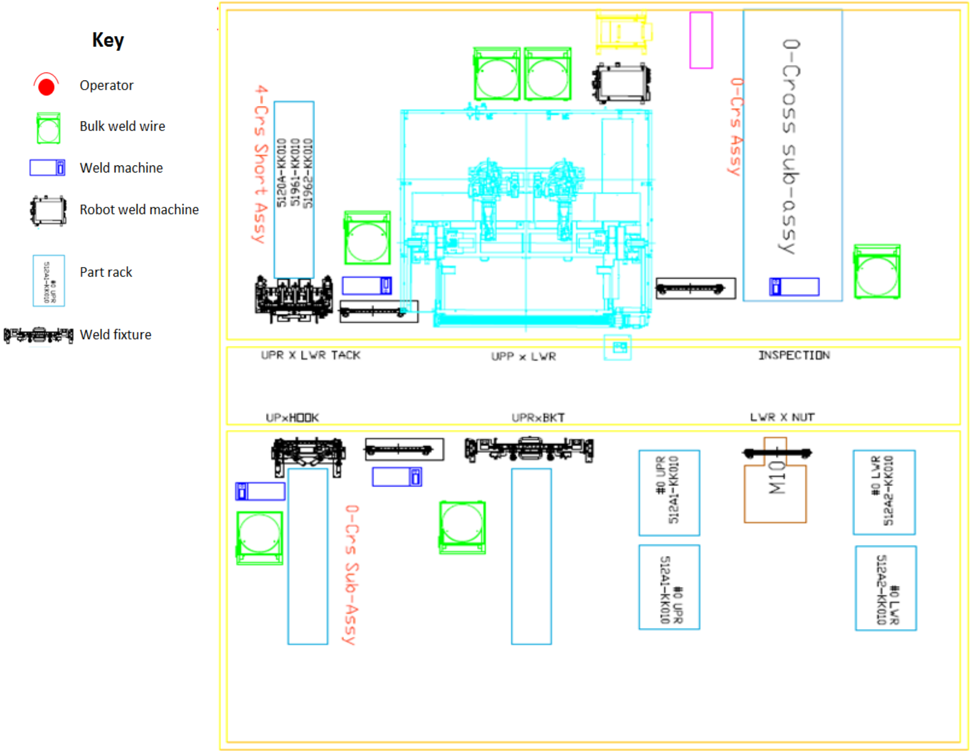


Figure 10: Auxiliary Cross production cell (Panter 2014)

3.6.2 Control Group

Experimental designs that included both treatment and control groups, and recorded information both before and after the experimental group was exposed to the treatment,were known as ex-post factor experimental designs (Sekaran and Bougie 2016).As mentioned above, the White and Yellow shifts were treated as control groups. The treatment group would be the Lean tools that were applied, and the effect would be the measurement of the GHG emissions. There was no unique constraint that would determine the control and experimental groups. In this instance, it would be the researcher's choice; hence, the WhiteShift would be the control group and the Yellow shift the experimental group.

The pre-test and post-test experimental and control group design explain this image in detail. The two shifts would be used as experimental and control groups. Both of these groups would be exposed to the pre-test and post-test measurements. The key difference between the groups would be that one group would receive the treatment in the form of Lean tool application, and the other would not. Measuring the difference between the post-test and pre-test scores would indicate the effect of the treatment. The followingtable further illustrates this:

Table 1: Control Group Design

<table>
<tr><th colspan="5">F_1 Value Stream Mapping</th></tr>
<tr><th>Group</th><th>Treatment</th><th>Pre-test</th><th>Post-test</th><th>Result</th></tr>
<tr><td>Experimental group</td><td rowspan="2">VSM</td><td>O_1</td><td>O_2</td><td rowspan="2">$[(O_2 - O_1)] - [(O_4 - O_3)]$</td></tr>
<tr><td>Control group</td><td>O_3</td><td>O_4</td></tr>
<tr><th colspan="5">F_2Total Productive Maintenance</th></tr>
<tr><th>Group</th><th>Treatment</th><th>Pre-test</th><th>Post-test</th><th>Result</th></tr>
<tr><td>Experimental group</td><td rowspan="2">TPM</td><td>O_5</td><td>O_6</td><td rowspan="2">$[(O_6 - O_5)] - [(O_8 - O_7)]$</td></tr>
<tr><td>Control group</td><td>O_7</td><td>O_8</td></tr>
<tr><th colspan="5">F_3Standardized Work</th></tr>
<tr><th>Group</th><th>Treatment</th><th>Pre-test</th><th>Post-test</th><th>Result</th></tr>
<tr><td>Experimental group</td><td rowspan="2">Standardized work</td><td>O_9</td><td>O_{10}</td><td rowspan="2">$[(O_{10} - O_9)] - [(O_{12} - O_{11})]$</td></tr>
<tr><td>Control group</td><td>O_{11}</td><td>O_{12}</td></tr>
</table>

3.6.3 Sample Size

Considering data from a sub-group, rather than from all possible cases and elements, was a technique that enabled one to reduce the amount of data that was required to be collected (Thornhill, Saunders and Lewis 2009). Based on customer demand, TSAM had a daily volume that was required to be met.In a mass production environment, this often required repetitivetasks by operators and machinery to achieve volume. Hence, the sample sizes of the experiments were based on a segment of the build volume, as they already consisted of repetitive cyclic work that could provide a consistent degree of data. Further to this, the repetitive work aided in improving the control over the experiment and reduced the chance of extraneous variables.

Using a sample size table with a 5% margin of error, the sample size for a daily volume of 210 units was interpolated to be 136 cycles. However, after a discussion with Production

Management, it was advised not to utilize this large a sample, as the measurements might cause disruption to production activities that could in turn pose a risk to quality and volume. Instead, the team opted for a one-hour window period each day to conduct the experiments and acquire the results. The one-hour window period allowed for 26 cycles and included measurement of $C0_2$ emissions and job observation.

3.7 Experiment Design

3.7.1 Preliminary Work - Experiment 1

In order to test the feasibility of the study, preliminary work in the form of a pre-test was conducted to determine whether the methodology adopted would meet the objectives of the study.Pre-testing was the first measure of the dependent variable and would support the test effects of the treatment.

Acknowledging the above, a pre-test was done on the Auxiliary Cross Member. A crucial requirement for the experiments to take place was the identification of major GHG contributors. Listing the services of the equipment in each process resulted in the following four key emitters:

- Compressed Air Usage

Compressed air was essential in order to supply process requirements and to operate pneumatic tools. It was relatively costly to generate and consumed a large share of the total energy consumption in industry (Mousavi, Kara and Kornfeld 2014). Similarly, the plant utilized compressed air in order to operate the weld fixtures. These weld fixtures make use of pneumatic cylinders to clamp and hold components in place during the weld process. Hence, the measurement of compressed air was required as it was a vital resource in the process operation.

- Electricity Consumption

The manufacturing community was a significant GHG emissioncontributor due to the intense use of electrical energy for industrial operations. Most of this energy in manufacturing was supplied in the form of electricity (Fysikopoulos *et al.* 2012). The welding process, the core function of the plant, was a considerable consumer of electricity.Additionally, the supply of compressed air ultimately leads to electricity consumption and contributes to the overall use of electricity.

- Shielding Gas for Weld Operations

The shielding gas used in welding processes significantly affected the weld geometry, seam appearance, mechanical propertiesand fume emission (Mvola and Kah 2017). The plant utilized a shielding gas mixture of $C0_2$ and Argon to protect the weld pool against contamination that could generate defects. The shielding gas is a direct emitter of $C0_2$into the environment, and the consumption would therefore be measured.

- Solid waste - Weld Wire Packaging

Gas Metal Arc Welding (GMAW) employed a wire electrode or filler as one of the consumables in the joining process (Marques *et al.* 2017). Parslow (2012) found that varying the weld parameters had a direct effect on electrical consumption and weld wire usage. Hence, any change to electrical consumption during the experiments mightaffect the weld wire consumption.

The consumption affects the environment in two particular ways; the first being the weld fume generation,which is out of the scope of this study due to the lack of equipment required to carry out fume measurements. The second way is the packaging of the weld wire, whichresults in landfill waste. Quantifying of the landfill equivalent waste was achievable and will be discussed in more detail under the Data Collection section.

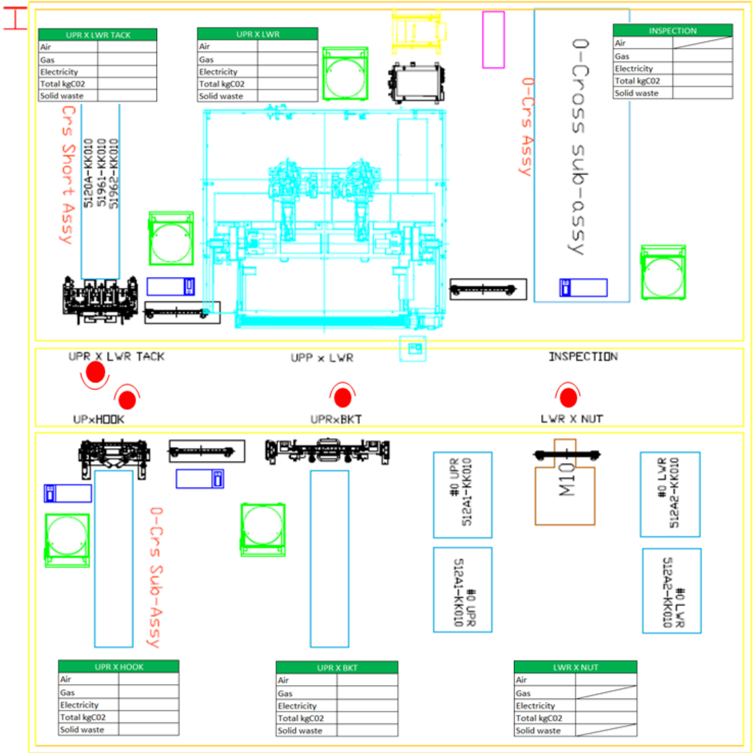


Figure 11: Auxiliary Cross member and GHG contributors. Adapted from Panter (2014); Chiarini (2014)

Figure 11 depicts the visualization of the GHG contributors by equipment type. The LWR x NUT stage does not make use of shielding gas and solid waste as it uses a form of resistance spot welding. The inspection stage does not have a pneumatic weld fixture, but rather a static weld table. Therefore, it does not make use of compressed air.

The operators and production standard equipment were utilized for this test. There was a concern that the operators would not understand the objective of the pre-test, and that would affect the internal and external validity of the study.Therefore, the objective of the study was presented to the operators to clarify any doubts. The pre-test study was conducted over a one-month periodand consisted of the following:

a) A cycle time study and movement analysis for online operators. The pre-test work would be based on the current work operation and would serve as the basis before Lean treatment was applied.The procedure consists of three stages and is detailed below:

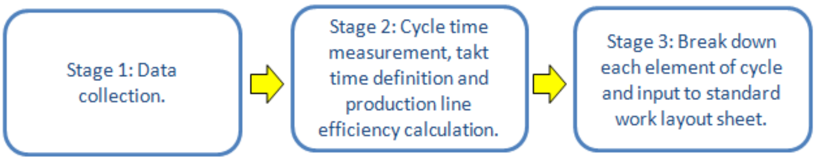


Figure 12: Cycle time measurement guideline. Adapted from Fin (2017)

During stage 1, all data regarding the project would be collected. This included production forecast, process plans and part assembly specification.

Stage 2 involved the measurement of cycle time for each operator including the automated stages. The production line takt was calculated by dividing the available time in a production shift by production demand per shift.

$$Takt\ time = \frac{Available\ production\ time}{Production\ demand_{shift}} \qquad (1)$$

Since there was a2-shift pattern in a working day, the production demand per shift would be calculated as follows:

$$Production\ Demand_{shift} = \frac{Total\ monthly\ volume}{No\ of\ days\ in\ a\ month \times 2} \qquad (2)$$

Using the cycle time data and the calculated takt time, the production line efficiency could be calculated.

$$Efficiency = \frac{Total\ work\ station\ cycle\ time}{Takt\ time\ \times\ no. of\ operators} \times 100 \qquad (3)$$

The cycle time would be broken down into elements during stage 3. This would be plotted on stacked graphs and compared to the takt line. The takt line was the absolute limit for the process. Elements above the takt line were constraints to the process. Along with the stack graph, the worker movement would be plotted, highlighting the progression of the operator activity through the cycle. The graphic representation was known as the Standard Work layout sheet and exposed wasteful activities while improving visualization.

b) Measurement of all services identified. The tools utilized are explained further in the Measuring Instruments section. The initial measurements served as the primary data before any Lean treatment was applied.

3.7.1.1 Measuring Instruments

The environmental impacts that make up the dependent variable were identified as compressed air, electricity, shieldinggas emissions and solid waste. During an energy audit process, clamp-on power meters, tachometers and mass flow meters were found to be some of the most effective measurement and auditing instruments (Saidur, Rahim and Hasanuzzaman 2010).In line with this study, similar types of tools were used to measure the environmental impacts. These are broken down further:

Table 2: Measuring instruments breakdown

Category	Measurement Tool	Unit of measure
1. Gas emissions	Mass flow meter	$kgC0_2$
2. Compressed air	Mass flow meter	$Nm^3/_{hr}$
3. Electricity	Clamp on power Logger	kWh
4. Solid waste	Weighing Scale	kg
	Tachometer	cm
5. Time	Stop Watch	$seconds$

Compressed air was required for the operation of the weld fixtures. These fixtures ran on a maximum of 6 bar pressure. The tool used to track the air usage of the production line was a mass flow meter (Hauser undated). TSAM currently utilizes a Proline T-Mass 65 by Endress + Hauser for all mass flow measurements. The meter has the ability to measure air, gas, Oxygen, Nitrogen, Carbon Dioxide and Argon. Given that the meter has the ability to measure a range of gases, the shielding gas would be measured in the same manner. Electricity is required for the use of the arc welding machines as well as the automated welding stages. A clamp-on power logger would be used to measure the electricity consumption of these facilities. TSAM makes use of a Hioki Clamp on a Hitester unit. These units have the ability to read 3-phase power systems and accurately measured the weld facilities (Corporation 2009).Solid waste measurement would be done by observing the weld wire consumption which was determined by the facility condition. The Shimpo DT-150A Tachometer was employed to measure the wire consumption during welding operations as it had the ability to measure linear speeds and the distance of objects (CORPORATION undated).

3.7.2 Value Stream Mapping - Experiment 2

The primary goal of VSM was to find different forms of waste and try to eliminate them (Rother and Shook 2003). Further to this, the literature review has demonstrated that VSM could be implemented to identify the environmental impacts for each process of the plant layout (Wills 2011).

Drawing a VSM map should follow a standard procedure so that all required data was captured (Chiarini 2014; Manjunath *et al.* 2014; Kurdve *et al.* 2015). The following steps should be carried out:

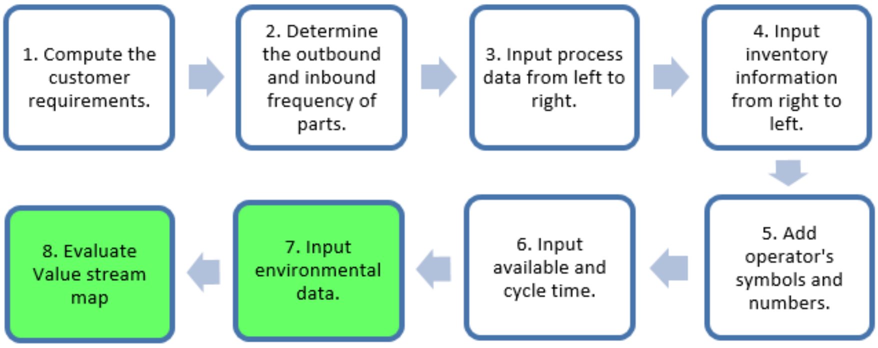


Figure 13: Value Stream map guideline. Adapted from Chiarini (2014)

Steps 1 through to 6 highlight the standard VSM procedure, while steps 7 and 8 supplement the map with environmental data. In order to reduce any misconception or ambiguity, the VSM would be done by physical online study and not make use of simulation-aided techniques.The areas with the Lean wastes and high energy consumptioncould be visualized through the map. The result of this experiment would support the theoretical findings of VSM.

3.7.3 Total Productive Maintenance - Experiment 3

TPM is a structured approach which utilizes a number of tools and techniques to achieve effective machinery and plants (Wakjira and Singh 2012). Through the affiliation with Toyota Motor Company, over the years TSAM has implemented a Lean thinking culture within the organisation. Hence, a TPM structure currently exists within the plant. By means of this structure, the aim of the experiment is to measure the before and after effect on machinery upon the completion of a TPM. The experiment will tie into the regular maintenance schedule to avoid production schedule conflicts.

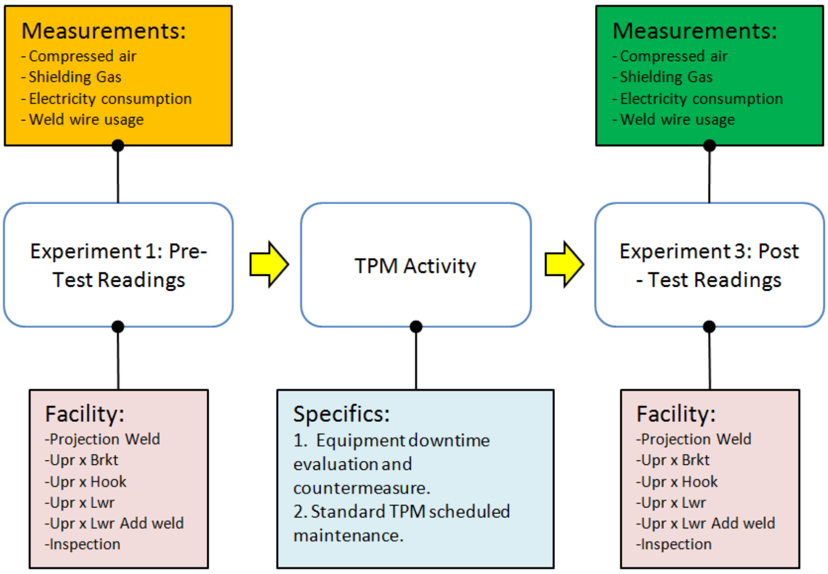


Figure 14: TPM Experiment guideline (Authors concept)

3.7.4 Standardized Work - Experiment 4

Standardized Work was the safest, easiest and most efficient way to perform a task. The goals werethe pursuit of high productivity through activities that were not difficult but wereefficient enough to eliminate inventory and wastes (Nallusamy 2016). Implementation of Standardized Work required the following steps to be carried out (Fin 2017):

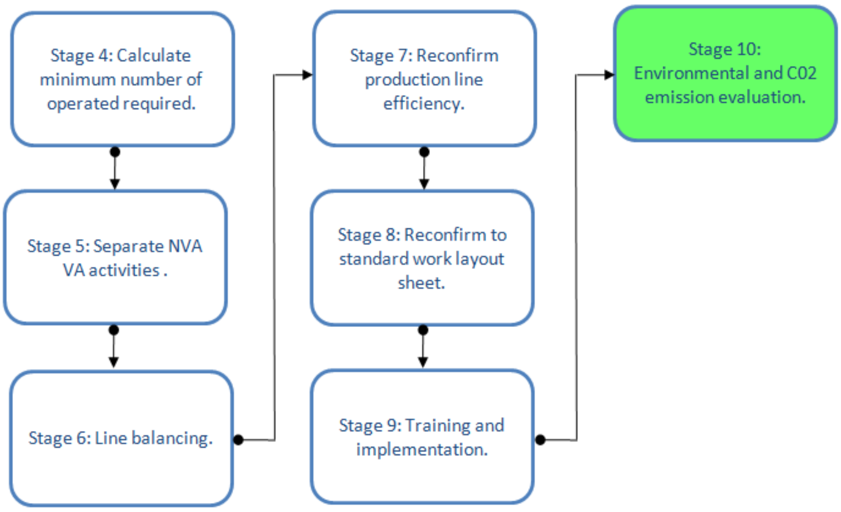


Figure 15: Standardized Work guideline. Adapted from Fin (2017)

The Standardized Work experiment was a continuation from experiment 1 and recommenced at stage 4. The stage involved the calculation of the minimum number of operators required for the production line to function. The following formula was used:

$$Manpower = \frac{Total\ work\ station\ cycle\ time}{Takt\ time} \qquad (4)$$

The minimum number of operators required was calculated by dividing the total cycle time of the line by the takt time.

Step 5 entailed a deeper understanding of the core work and involved categorizing elements into Value Adding Work, which changed the shape and properties of the product, Necessary Work, which was required but did not add value, and Non Value Adding work which waswork that did not add value to the product (Sabadka *et al.* 2017).

The line balancing activity in Stage 6 allowed for an even distribution of work content across the production line and improved utilization.

Stages 7 and 8 allowed for the reconfirmation of the production line efficiency and Standard Work layout sheet. The reconfirmation allowed one to visualize the improvements and aids, and confirmedwhether the efficiency was heading in the desired direction.

Stage 9 involved training and implementation of the improvement activity. The training supported a smooth transition through the change points and minimized any quality or productivity problems.

Stage 10 dealt with the re-confirmation of the GHG contributors to evaluate the effect of the experiment. All processes would be remeasured and results tabulated.

3.8 Validity and Reliability

For the purposes of this study, internal and external validity was applicable. Internal validity referred to the confidence one placed in the cause-and-effect relationship. More specifically, it evaluated to what degree the independent variable affected the dependent variable. High internal validity was usually associated with laboratory experiments where cause-and-effect relationships were substantiated (Sekaran and Bougie 2016).

External validity differed as it referred to the extent to which the results of a causal study could be generalised to and across other settings, people or events. Field experiments commonly had more external validity(Morin-Chassé and Lachapelle 2015). For the purposes of this study, external validity would be used, as it best suits field experiments.

3.9 Data Collection Methods

Experiments were devised to answer unique questions and often required the development of measurement systems to obtain relevant data (Andersson 2012). As stated previously, the study was based on field experiments and would provide quantitative data. The results obtained would serve as primary data as they were collected from first hand experience and dealt specifically with the problem under study (Kabir 2016).

In this study the data would be collected using the specified measuring instruments over the 26 samples for the $C0_2$ emitters. The data would be averaged out in acquiring the mean emission generated per process. Once the mean for each $C0_2$ emitter had been calculated per process, a common unit of measure wouldneed to be established to support the interpretation and judging criteria.

The total amount of GHG emissions produced directly and indirectly was known as the carbon footprint andwas commonly measured in kilograms of carbon dioxide ($kgC0_2$)(Mohajan 2017). With this in mind, the following was taken into account when commonizing the unit measure:

- Compressed Air Consumption

The Endress Hauser meter provided the results in a unit measure of normal cubic metres per hour ($^{Nm^3}/_{hr}$). However, the GHG emission took place at the plant compressor unit. Therefore, the unit provided by the meter would need to be converted to kilowatt-hour (kWh) and thereafter to $kgC0_2$. The compressor efficiency factor was detailed as 0.155 on the plant's compressor housing and related to the electricity consumption. The efficiency factor can be detailed as 0.155 kWh produced for every 1 $^{Nm^3}/_{hr}$ used. Therefore by multiplying this constant by meter readings, the power consumption in kilowatt-hours was obtained:

$$\overline{\text{X}}\ ^{Nm^3}/_{hr} \times 0.155 = \overline{\text{X}}\ kWh \qquad (5)$$

In order to obtain the unit of $kgC0_2$, the Carbon Dioxide emission factor specific to South Africa's energy provider, Eskom, needed to be understood. The emission factor, based on a study of three of the country's base-load coal fired power stations was calculated to be 0.955 $kgC0_2$ per kWh electricity generated (Letete, Guma and Marquard 2010).

$$\overline{\text{X}}\ kWh \times 0.955\ ^{kgC0_2}/_{kWh} = \overline{\text{X}}\ kgC0_2 \qquad (6)$$

Based on the above formula and constants, the compressed air consumption could be represented as kilogramsofCarbon Dioxide($kgC0_2$).

- Electricity Usage

The clamp-on power logger already provided results in a unit measure of kWh. Following the same line of thinking, convertingto $kgC0_2$ would be the same as described in the compressed air consumption section.

- Shielding Gas Consumption

The Endress Hauser meter would once again be utilized; however, it wouldbe calibrated to yield mass flow in a unit measure of $kgC0_2$. Therefore, the results obtainedwould not need any conversion and could be used in the format measured.

- Weld Wire Consumption

Currently weld wire wass purchased in bulk packs due to production volume requirements. The bulk packs contain $250kg$ worth of weld wire packaged in cardboard drums. The packaging material accounts for an additional $8.6kg$ worth of cardboard. When the wire has been used, the packaging can be disposed of at landfill sites.

The change in weld parameters or electricity usage for weld machines could have a positive or negative effect on the amount of weld wire utilized. Ultimately this would lead to a change in the amount of solid waste being sent to landfill sites and should therefore be understood.

Using the Shimpo - DT - 150A tachometer and a weighing scale, it was found the $1m$ of wire equated to $8.7\ grams$ of wire or $0.0087\ kg$. Since landfill wastes are quantified in kilograms, the ratio could be measured and converted to a common unit that allowedfor the understanding of solid waste by weld wire usage.

It was critical to understand the usage of weld wire at each process. In order to carry this out the following formula would be used:

$$\overline{\mathrm{X}}/100 \times 0.0087 = \overline{\mathrm{X}}\ wire\ usage\ kg \qquad (7)$$

Since the measurement unit of the tachometer was cm, it was coverted to meters by dividing by $\overline{\mathrm{X}}$ by 100. The sum of the mean wire usage per process would result in the mean usage per AuxiliaryCross member manufactured. Therefore,the Monthly production volume multiplied by the mean usage per Auxiliary Cross member would result in the Monthly consumption of wire and disposal of packaging material to landfill sites.

$$\Sigma\overline{\mathrm{X}}\ wire\ usage\ kg\ \times Monthly\ production\ volume = Monthly\ consumption\ kg \tag{8}$$

Monitoring the monthly consumption of wire would allow for further interpretation of how Lean tools affected the environment.

3.10 Conclusion

The chapter has described a quantitative study to understand the cause and effect of Lean tools on carbon emissions. Four field experiments would be carried out and have been described in detail in the chapter. The control and experimental groups have been discussed to ensure that the effects of the treatment of each Lean tool applied to the carbon emissions could be determined. The sample characteristics supported those of the production environment to ensure minimaldisruptions to the production operation.

The chapter additionally described the conceptual framework, the background to the experiment setting, measuring instruments and data collection methods to ensure the reliability and validity of the study.

Chapter 4

Analysis of Results and Discussion of Findings

4.1 Introduction

This chapter presents the Lean application, the results and a discussion of the findings obtained from the study. The results are presented in the form of graphs, tables and figures. The layout of the chapter consists of four key sections that include the results of each experiment pertaining to each theoretical finding. The sections are as follows: Pre-test work, Value Stream Mapping, Total Productive Maintenance and Standardized Work.

Each experiment follows a consecutive order and the results are carried from one experiment to the next. A Value Stream Map has been included at the end of Experiments 2 and 3 to depict the overall effect of the applied Lean tool. A summary will be presented at the end of this chapter.

4.2 Experiment 1 - Pre-test

The pre-test was conducted to obtain an understanding and a measurement of the dependent variable. This formed the primary data of the investigation and allowed for the monitoring of change as each independent variable was applied.

Before measuring the emission emitted within the line, the production process was studied to acquire a deeper understanding of the operation. Due to the sequence of activities supporting the visualization of processes, rating of productivity and reduction of variability, the Standardized Work Theory was applied(Mariz *et al.* 2012).

4.2.1 Standardized Work

The Standardized Work procedure has been highlighted in the methodology section. For experiment 1, only steps 1 through to 3 were utilized, as only the current condition needed to be clearly visualized.

4.2.1.1 Stage 1 - Data Collection

The data collection entailed understanding the components used to build the assembly, the sequenced process of the assembly, and the production forecast to understand the required build rate.

4.2.1.1.1 Assembly and components

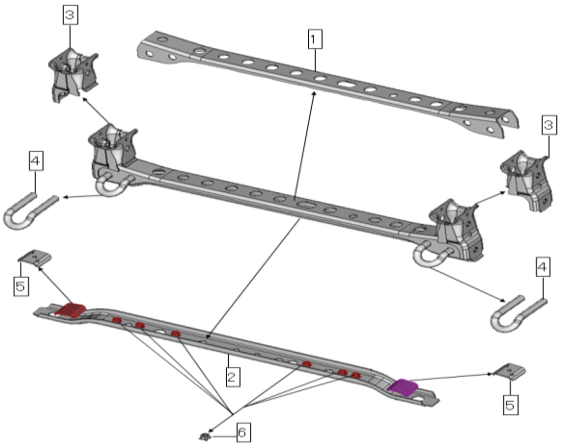


Figure 16: Exploded view of Auxiliary Cross member (Tanaka 2014)

Table 3: Auxiliary cross member bill of materials

SERIAL No.	PART No.	PART NAME	QTY
1	512A1-KK010	CROSS MEMBER, FRAME AUXILIARY, UPR	1
2	512A2-KK010	CROSS MEMBER, FRAME AUXILIARY, LWR	1
3	5120A-KK010	GUSSET SUB-ASSY, FRAME AUXILIARY C/MBR, RH	2
4	51961-KK010	HOOK, FR	2
5	51962-KK010	RETAINER, FR HOOK	2
6	90174-T0004	NUT, WELD	6

Figure 16 and Table 3 illustrate the exploded view of the Auxiliary Cross Member as well as the bill of materials. There are 14 components required to complete the assembly. The exploded view provides an image of the orientation and assembly of the components. The process plan further clarifies the assembly sequence of each component.

4.2.1.1.2 Process plan

The process plan was a preparatory step and drew attention to the sequence of operations. It was frequently used in manufacturing shops that made parts of the same kind on a regular basis (Newman *et al.* 2012). The process plan for the Auxiliary Cross Member is shown below:

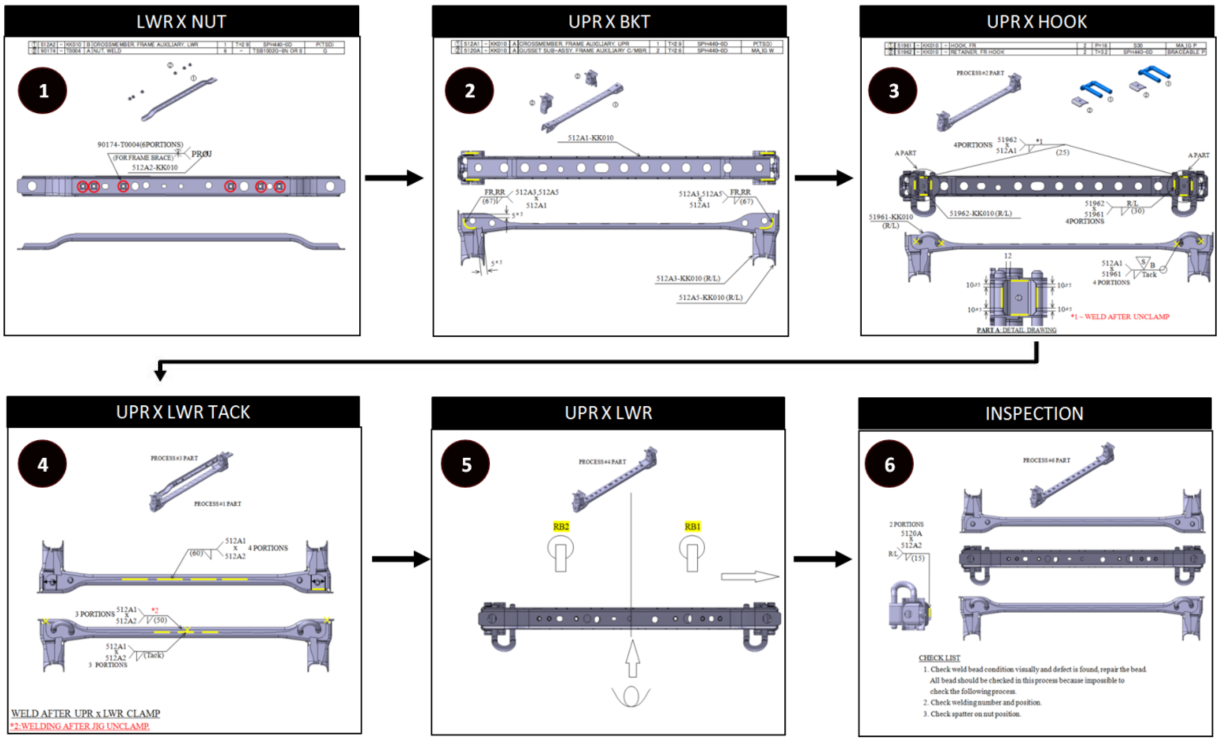
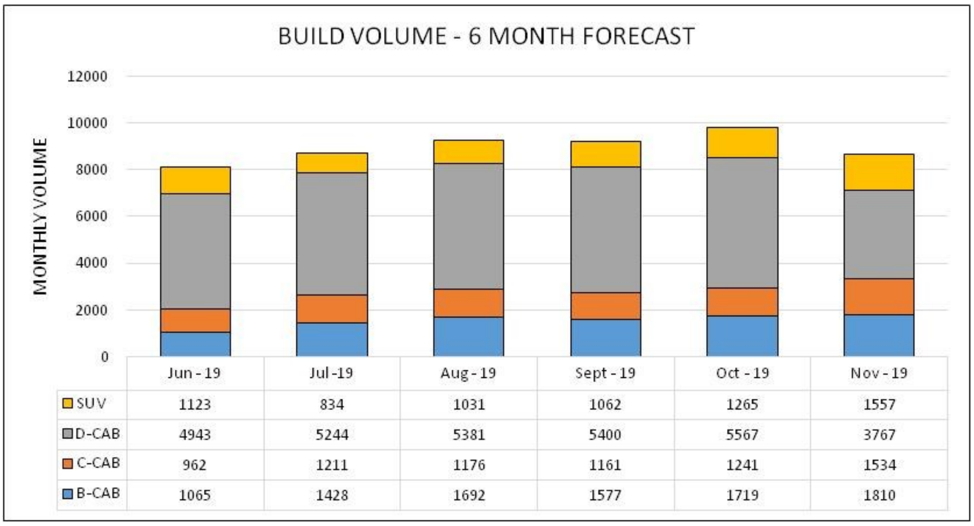


Figure 17: Auxiliary Cross process plan (Tanaka 2014)

The process plan in Figure 17 highlights the series of steps that were followed to complete the weld operation of the Auxiliary Cross Member. Each stage details the specific parts and respective quantities, the assembly process, and the required weld elements. These key points provided fundamental information to help ensure that the quality requirement was met within the optimum cycle time.

4.2.1.1.3 Production demand

Utilizing supply chain production planning methods, the demand planning could be forecasted for manufacturing volume purposes (Mula, Peidro and Poler 2010). This is comparable to TSAM as the forecasted volumes are based on the sales information provided by the dealerships. Through the marketing and sales, and production planning departments, this information is thoroughly analysed before forecast generation. For this study, the following information was obtained from the production planning department:



	Jun - 19	Jul -19	Aug - 19	Sept - 19	Oct - 19	Nov - 19
SUV	1123	834	1031	1062	1265	1557
D-CAB	4943	5244	5381	5400	5567	3767
C-CAB	962	1211	1176	1161	1241	1534
B-CAB	1065	1428	1692	1577	1719	1810

Graph 1: 6 Month Volume Forecast

The monthly volume by IMV model type is illustrated in Graph 1. The average volume per month is 8958 units. As mentioned in the methodology, the Auxiliary Cross is required for all model types hence the total volume represents the production demand.

The assembly and components, process plan and production demand help to conceptualize the requirements of the line. The information additionally supports Step 2 in the calculation of takt and cycle time.

4.2.1.2 Stage 2 - Takt time, Cycle time and Line Efficiency

Takt and cycle time were imperative elements in improving productivity, reducing cost and improving customer response (Kumar and Kumar 2014). They therefore provided a visualization of the production line capability, which formed the basis for improvements to take place.

4.2.1.2.1 Takt time

Step 1 highlighted the production volume, which was used to calculate the takt time via the following formula:

$$Takt\ time = \frac{Available\ production\ time}{Production\ demand_{shift}} \qquad (1)$$

The production shift was 7.5 hours of working time and this equated to 450 minutes. The monthly volume per day would need to be calculated by volume per shift,

$$Production\ Demand_{shift} = \frac{Total\ monthly\ Volume}{No\ of\ days\ in\ a\ month \times 2} \qquad (2)$$

Since there were two shifts in a working day, the formula has a division of 2. Table 4 demonstrates the use of these formulas.

Table 4: Monthly takt time calculation

Body and Chassis Type						
Category	Jun - 19	Jul -19	Aug - 19	Sept - 19	Oct - 19	Nov - 19
B-CAB	1065	1428	1692	1577	1719	1810
C-CAB	962	1211	1176	1161	1241	1534
D-CAB	4943	5244	5381	5400	5567	3767
SUV	1123	834	1031	1062	1265	1557
Total Monthly Volume	8093	8717	9280	9199	9792	8668
No. of days per month	20	23	22	21	23	21
Takt Calculation						
Production Demand$_{shift}$	203	190	211	220	213	207
Takt time	2,22	2,37	2,13	2,05	2,11	2,18

The takt time varies as the market demand changes from month to month. In this case, the lowest takt time was used to ensure the production lines had enough flexibility to adjust to the demand variation.

The takt time of 2.05 minutes or 123 seconds was the time required for a unit to be produced at the end of the manufacturing process. Therefore, to meet the requirement, TCP required a lower takt process.

The standard TSAM process is to reduce an additional 3 seconds from the preceding process to cater for the delivery time. The figure below better describes this:

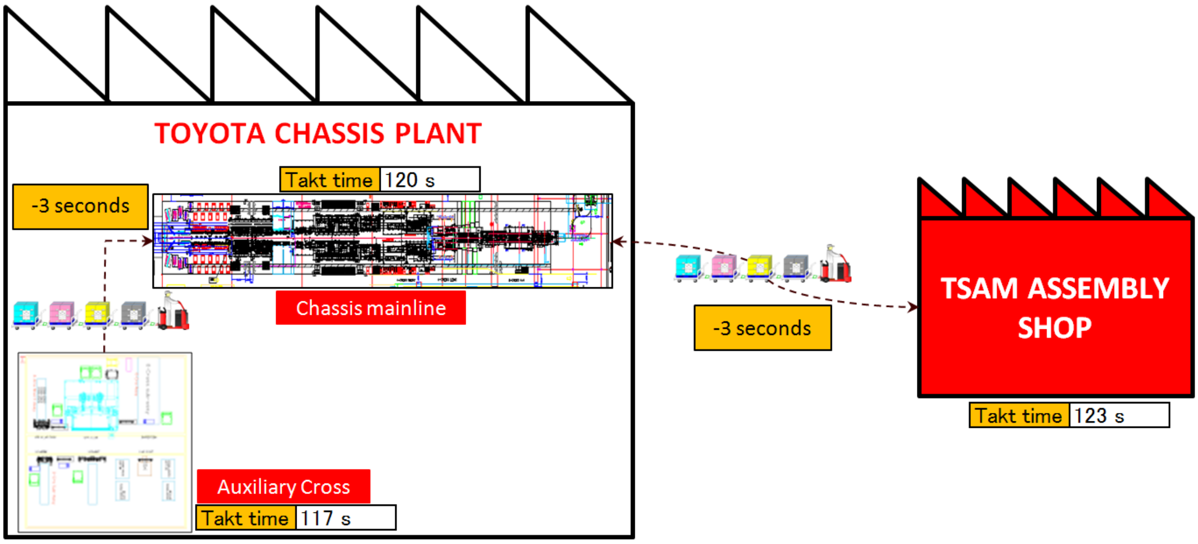


Figure 18: Takt time and delivery time (Authors concept)

The Assembly plant would manufacture at a takt time of 123 seconds. TCP as the preceding process would therefore run at 120 seconds. This refers to the Chassis Mainline as described in the methodology. The Auxiliary Cross Member was supplied to the Chassis Mainline and would therefore undergo a further 3-second reduction in takt time. Thus, the overall takt time pace that the Auxiliary Cross should manufacture to was 117 seconds.

4.2.1.2.2 Cycle time

The cycle time measurement was recorded by timing the operator from the start to the finish of their work cycle. This was done over 26 cycles with each operator.

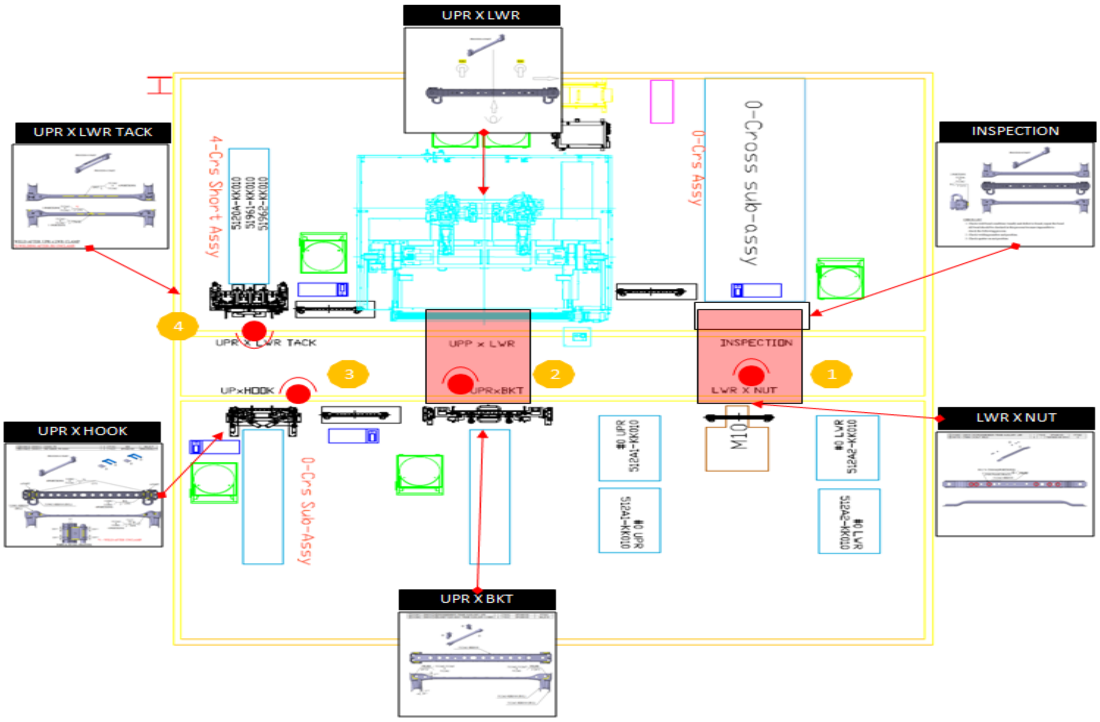


Figure 19: Process plan breakdown. Adapted from Panter (2014); Tanaka (2014)

Figure 19 illustrates each of the process plan stages paired with the respective equipment. This provided a clearer understanding of the worker movement and processes completed within the cycle. The figure additionally showed that operators 1 and 2 had multiple tasks as they completed two stages within their cycles.

The cyclic work of each of the operators was video recorded. The videos were then studied and broken down to element phase. The cycle times for each of the operators are listed below:

Operator 1

Table 5: Operator 1 cycle time measurement

No.	ELEMENT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	MAX	MIN	MEAN
1	Pick up and set Auxiliary cross on table	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
2	Torch and sheild preperation	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
3	Weld(2 x 15mm)	6.1	6.0	5.9	6.1	5.9	6.0	6.2	6.0	5.9	6.0	6.0	5.9	5.9	6.0	5.9	6.1	5.9	6.0	6.0	6.1	6.0	5.9	6.1	6.0	6.1	6.1	6.2	5.9	6.0
4	Return torch and sheild	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
5	Pick up marker	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6	Weld inspection(2 x 15mm)	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
7	Rotate part	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
8	Inspection (1,030mm welds)	10.5	10.3	10.1	10.5	10.1	10.4	10.6	10.3	10.2	10.4	10.4	10.2	10.2	10.3	10.1	10.4	10.2	10.4	10.3	10.4	10.3	10.1	10.4	10.3	10.5	10.5	10.6	10.1	10.3
9	Rotate part	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10	Return marker	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11	Pick up Nut gauge	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12	Inspection (10 Nuts)	18.3	17.9	17.7	18.3	17.7	18.1	18.5	18.0	17.8	18.1	18.1	17.8	17.8	18.0	17.6	18.2	17.8	18.1	18.0	18.2	18.0	17.7	18.3	18.0	18.3	18.3	18.5	17.6	18.0
13	Return nut gauge and load Auxiliary cross on FG rack	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
14	Walk to Lwr Nut stage	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0
15	Pick up Upper Auxiliary Cross	5.1	5.0	4.9	5.1	4.9	5.0	5.2	5.0	5.0	5.0	5.0	5.0	4.9	5.0	4.9	5.1	4.9	5.0	5.0	5.1	5.0	4.9	5.1	5.0	5.1	5.1	5.2	4.9	5.0
16	Nut weld set	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
17	Nut weld (*6 Nuts)	18.3	17.9	17.7	18.3	17.7	18.1	18.5	18.0	17.8	18.1	18.1	17.8	17.8	18.0	17.6	18.2	17.8	18.1	18.0	18.2	18.0	17.7	18.3	18.0	18.3	18.3	18.5	17.6	18.0
18	Pick Up marker	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
19	Inspect *6 nuts	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
20	Return marker	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
21	Take out part and transfer	3.1	3.0	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.1	2.9	3.0
	TOTAL	89.9	87.9	86.9	89.6	86.9	89.0	90.9	88.3	87.4	88.7	88.9	87.4	87.3	88.1	86.5	89.4	87.2	88.8	88.3	89.3	88.3	86.8	89.5	88.3	89.7	90.0	90.9	86.5	88.3

Operator 1 had a multistage process in that LWR x NUT and INSPECTION were included in the cyclic work. The maximum and minimum cycle times recorded were 90.9 seconds and 86.5 seconds respectively, providing a 5% fluctuation rate. The mean cycle time was calculated to be 88.3 seconds.

Operator 2

Table 6: Operator 2 cycle time measurement

No.	ELEMENT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	MAX	MIN	MEAN
1	Pick and set Gussets (x2)	4.0	4.2	4.1	4.1	3.9	4.0	4.0	3.9	4.1	3.9	4.0	4.1	4.0	3.9	4.0	4.0	4.0	3.9	4.1	4.1	3.9	4.1	4.0	4.0	4.0	4.1	4.2	3.9	4.0
2	Walk to Pick upper	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
3	Set cross upper	3.0	3.1	3.0	3.1	2.9	3.0	3.0	2.9	3.0	2.9	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.1	3.1	2.9	3.1	3.0	3.0	3.0	3.1	3.1	2.9	3.0
4	Push button to clamp	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
5	Prepare touch and shield	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
6	Weld 67mm （RH)	8.0	8.3	8.1	8.2	7.8	8.0	7.9	7.8	8.1	7.8	8.1	8.1	8.0	7.8	8.0	8.0	8.0	7.9	8.2	8.2	7.8	8.3	8.0	8.0	8.0	8.3	8.3	7.8	8.0
7	Weld 67mm （LH)	7.0	7.3	7.1	7.2	6.8	7.0	6.9	6.8	7.1	6.8	7.1	7.1	7.0	6.9	7.0	7.0	7.0	6.9	7.1	7.1	6.9	7.2	7.0	7.0	7.0	7.2	7.3	6.8	7.0
8	Rotate Jig	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
9	Weld 67mm （RH)	7.0	7.3	7.1	7.2	6.8	7.0	6.9	6.8	7.5	6.8	7.1	7.1	7.0	6.9	7.0	7.0	7.0	6.9	7.1	7.1	6.9	7.2	7.0	7.0	7.0	7.2	7.5	6.8	7.0
10	Weld 67mm （LH)	8.0	8.3	8.1	8.2	7.8	8.0	7.9	7.8	8.1	7.8	8.1	8.1	8.0	7.8	8.0	8.0	8.0	7.9	8.2	8.2	7.8	8.3	8.0	8.0	8.0	8.3	8.3	7.8	8.0
11	Rotate Jig to home position	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
12	Shield and torch return	2.5	2.6	2.5	2.6	2.4	2.5	2.5	2.4	2.5	2.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.6	2.5	2.5	2.6	2.5	2.5	2.5	2.6	2.6	2.4	2.5
13	Press push button to unclamp	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
14	Take out part and set on catch tray	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
15	Pick up torch and shield	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
16	Arc weld (25mm*2)	6.0	6.2	6.1	6.2	5.8	6.0	5.9	5.8	6.1	5.9	6.0	6.1	6.0	5.9	6.0	6.0	6.0	5.9	6.1	6.1	5.9	6.2	6.0	6.0	6.0	6.2	6.2	5.8	6.0
17	Return torch and shield	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
18	Pick up Upper	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
19	Walk to robot	3.0	3.1	3.0	3.1	2.9	3.0	3.0	2.9	3.0	2.9	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.1	3.1	2.9	3.1	3.0	3.0	3.0	3.1	3.1	2.9	3.0
20	Tranfer welded Crossmember	5.0	5.2	5.1	5.2	4.9	5.0	5.0	4.9	5.1	4.9	5.0	5.1	5.0	4.9	5.0	5.0	5.0	4.9	5.1	5.1	4.9	5.2	5.0	5.0	5.0	5.2	5.2	4.9	5.0
21	Load boxed cross member	6.0	6.2	6.1	6.2	5.8	6.0	5.9	5.8	6.1	5.9	6.0	6.1	6.0	5.9	6.0	6.0	6.0	5.9	6.1	6.1	5.9	6.2	6.0	6.0	6.0	6.2	6.2	5.8	6.0
22	Press robot start	2.0	2.1	2.0	2.1	1.9	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1	2.1	1.9	2.0
23	Walk	3.0	3.1	3.0	3.1	2.9	3.0	3.0	2.9	3.0	2.9	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.0	3.1	3.1	2.9	3.1	3.0	3.0	3.0	3.1	3.1	2.9	3.0
	TOTAL	84.5	87.9	85.9	87.1	82.2	84.5	83.7	82.0	86.2	82.5	85.2	85.8	84.5	82.9	84.1	84.5	84.2	83.4	86.2	86.1	82.8	87.2	84.5	84.5	84.5	87.5	87.9	82.0	84.5

Operator 2 had a multistage process as well, where the UPR x BKT and loading for the automated UPR x LWR stage were included in the cyclic work. The maximum and minimum cycle times recorded were 87.9 seconds and 82.0 seconds respectively, providing a 7.2 % fluctuation rate. The mean cycle time was calculated to be 84.5 seconds.

Operator 3

Table 7: Operator 3 cycle time measurement

No.	ELEMENT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	MAX	MIN	MEAN
1	Pick up and set Cross S/A	3.0	3.0	3.0	3.0	3.1	3.1	2.9	3.0	3.0	2.9	3.0	2.9	3.0	3.0	2.9	3.0	3.0	3.1	2.9	3.0	3.0	3.1	3.2	3.1	2.9	3.0	3.2	2.9	3.0
2	Pick up and set small parts (Hook/Retainer)	20.0	20.2	20.3	20.0	20.4	20.4	19.5	20.2	20.3	19.6	20.0	19.2	20.0	20.2	19.6	19.7	19.9	20.6	19.6	20.0	19.9	20.4	21.0	20.7	19.3	20.3	21.0	19.2	20.0
3	Press PB (Clamp)	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.1	1.9	2.0	2.1	1.9	2.0
4	Shield and torch prep	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.1	1.9	2.0	2.1	1.9	2.0
5	Arc Welding RH (30mm*4)(25mm*2)	25.0	25.3	25.4	25.0	25.5	25.5	24.3	25.2	25.4	24.5	25.0	24.0	25.0	25.3	24.5	24.7	24.9	25.8	24.5	25.0	24.9	25.6	26.3	25.9	24.2	25.4	26.3	24.0	25.0
6	Tack weld (*4)	10.0	10.1	10.2	10.0	10.2	10.2	9.7	10.1	10.2	9.8	10.0	9.6	10.0	10.1	9.8	9.9	10.0	10.3	9.8	10.0	10.0	10.2	10.5	10.4	9.7	10.2	10.5	9.6	10.0
7	Return torch and shield	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.1	1.9	2.0	2.1	1.9	2.0
8	Press PB (Unclamp)	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.1	1.9	2.0	2.1	1.9	2.0
9	Shield and torch prep	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.1	1.9	2.0	2.1	1.9	2.0
10	Arc weld (25mm*2)	8.0	8.1	8.1	8.0	8.2	8.2	7.8	8.1	8.1	7.8	8.0	7.7	8.0	8.1	7.8	7.9	8.0	8.2	7.8	8.0	8.0	8.2	8.4	8.3	7.7	8.1	8.4	7.7	8.0
11	Take out Upper and transfer	5.0	5.1	5.1	5.0	5.1	5.1	4.9	5.0	5.1	4.9	5.0	4.8	5.0	5.1	4.9	4.9	5.0	5.2	4.9	5.0	5.0	5.1	5.3	5.2	4.8	5.1	5.3	4.8	5.0
12	Walk	6.0	6.1	6.1	6.0	6.1	6.1	5.8	6.0	6.1	5.9	6.0	5.8	6.0	6.1	5.9	5.9	6.0	6.2	5.9	6.0	6.0	6.1	6.3	6.2	5.8	6.1	6.3	5.8	6.0
	TOTAL	87.0	87.9	88.3	87.0	88.7	88.7	84.7	87.7	88.4	85.3	87.0	83.5	87.0	87.9	85.3	85.9	86.7	89.7	85.3	87.0	86.6	88.9	91.4	90.0	84.0	88.4	91.4	83.5	87.0

Operator 3 completed only the UPR x HOOK process. The maximum and minimum cycle times recorded were 91.4 seconds and 83.5 seconds respectively, providing a 9.3% fluctuation rate. The mean cycle time was calculated to be 87.0 seconds.

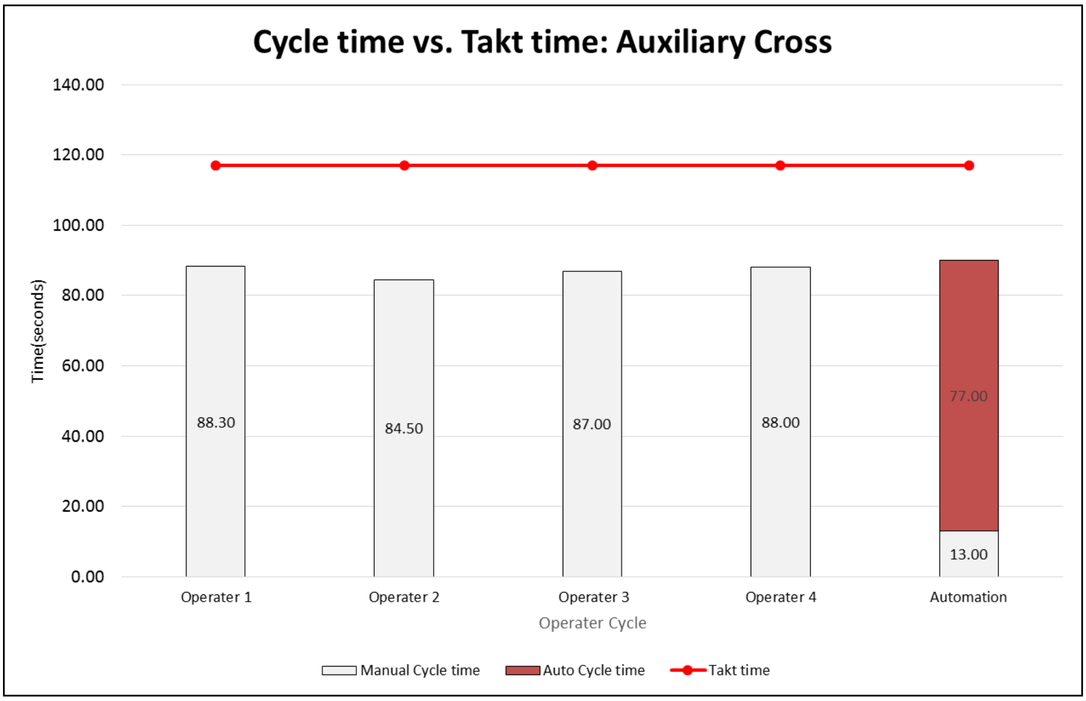
Operator 4

Table 8: Operator 4 cycle time measurement

No.	ELEMENT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	MAX	MIN	MEAN
1	Pick upper part from shute	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
2	Walk	2.2	2.0	2.0	2.1	2.0	2.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	1.9	2.0	2.0	1.9	1.9	2.0	2.0	2.2	1.9	2.0
3	Load part on jig	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
4	Walk	2.2	2.0	2.0	2.1	2.0	2.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	1.9	2.0	2.0	1.9	1.9	2.0	2.0	2.2	1.9	2.0
5	Pick lower part from jig	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
6	Walk	2.2	2.0	2.0	2.1	2.0	2.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	1.9	2.0	2.0	1.9	1.9	2.0	2.0	2.2	1.9	2.0
7	Load part and box	6.6	6.0	5.9	6.2	5.9	6.5	6.1	6.1	6.0	6.0	5.9	6.1	5.9	5.9	6.0	6.1	6.0	6.3	5.9	5.8	6.1	6.1	5.8	5.8	6.0	6.0	6.6	5.8	6.0
8	Press and activate clamps	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
9	Torch and Sheild Preperation	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
10	Tack weld x3 + (4x60mm)	35.2	31.9	31.4	33.1	31.7	34.6	32.3	32.6	32.0	32.0	31.6	32.5	31.7	31.4	32.0	32.6	32.3	33.6	31.3	30.7	32.6	32.7	31.0	31.1	32.0	32.0	35.2	30.7	32.0
11	Unclamp jig	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
12	Remove part, and lay on weld stand	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
13	Complete welding(3x50mm)	18.7	16.9	16.7	17.6	16.8	18.4	17.2	17.3	17.0	17.0	16.8	17.3	16.8	16.7	17.0	17.3	17.1	17.9	16.6	16.3	17.3	17.4	16.5	16.5	17.0	17.0	18.7	16.3	17.0
14	Return torch and sheild	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
15	Transfer part to robot shute	3.3	3.0	2.9	3.1	3.0	3.2	3.0	3.1	3.0	3.0	3.0	3.0	3.0	2.9	3.0	3.1	3.0	3.2	2.9	2.9	3.1	3.1	2.9	2.9	3.0	3.0	3.3	2.9	3.0
	TOTAL	96.8	87.7	86.2	91.1	87.1	95.2	88.9	89.6	88.0	88.0	87.0	89.4	87.1	86.3	88.0	89.6	88.7	92.5	86.1	84.4	89.7	89.9	85.2	85.4	88.0	88.0	96.8	84.4	88.0

Operator 4 completed only the UPR x LWR Tack process. The maximum and minimum cycle times recorded were 96.8 seconds and 84.4 seconds respectively, providing a 14.7% fluctuation rate. The mean cycle time was calculated to be 88 seconds.

At the automation stage, UPR x LWR provided a reading of 77 seconds. This process was timed twice and showed 0% fluctuation.



Graph 2: Cycle Time vs Takt Time

Graph 2 compares the mean cycle times to the takt time of the production line. The graphic representation assisted in the understanding of the line performance. Currently all operators were below the takt line, which illustrated that there were no bottlenecks and the production line could adequately manufacture the required volume.

4.2.1.2.3 Line efficiency

An important performance metric that should be tracked was the production line efficiency(Adnan, Arbaai and Ismail 2016). This metric describes the ratio of the current productivity level in relation to the best productivity level. The generally required productivity level of TSAM is 95% and provides one with the ability to rate the line. The formula below describes the efficiency calculation:

$$Efficiency = \frac{Total\ work\ station\ cycle\ time}{Takt\ time\ \times\ no.of\ operators} \times 100 \qquad (3)$$

$$Efficiency = \frac{88.3 + 84.5 + 87 + 88}{117\ \times\ 4} \times 100$$

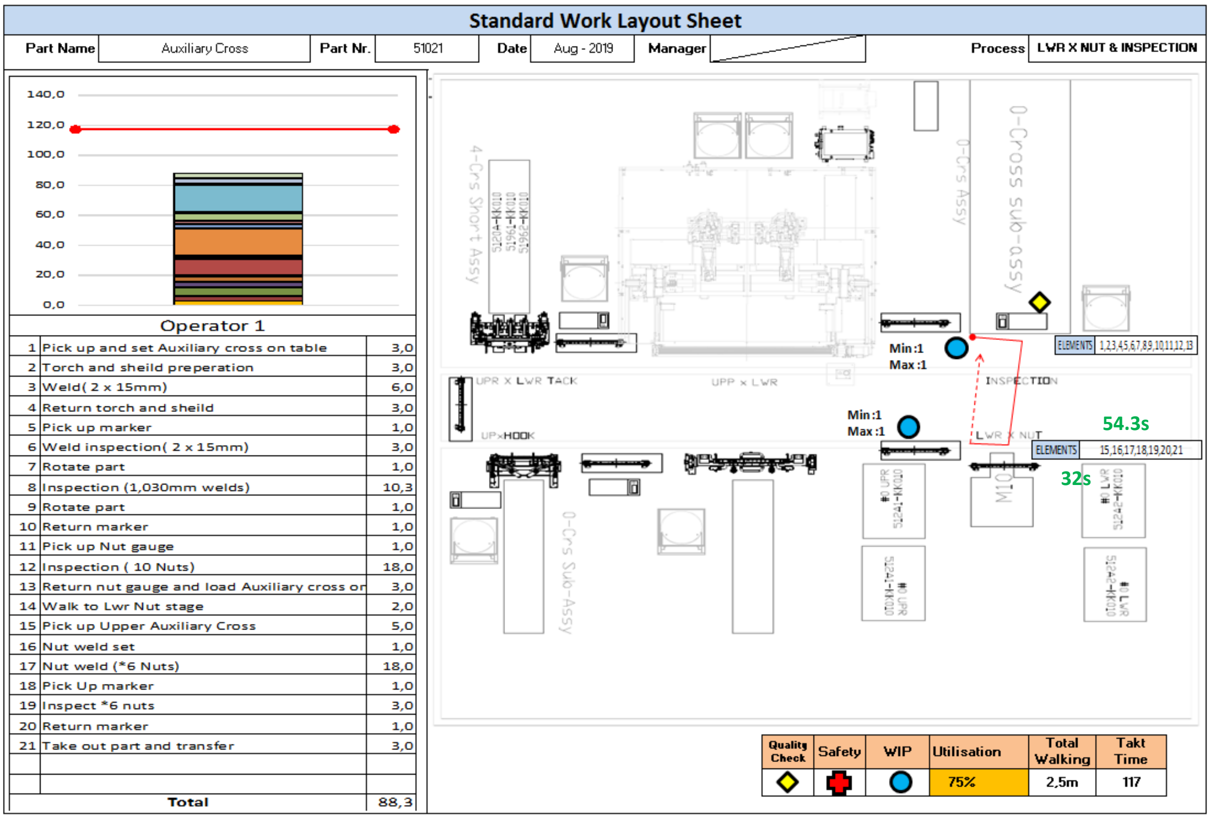
$$Efficiency = 74.3\ \%$$

The production line had an efficiency of 74.3% based on the current cycle and takt time. Compared to the general metric of 95%, the line had approximately 20% more capability and low operator utilization.

4.2.1.3 Stage 3 - Standard work layout sheet

Step 3 included the creation of the standardized work layout sheet. In creating the standardized work document, the work steps needed to be identified and recorded using a standardized work layout sheet which stated the work elements, the time elements and the operation as a graph (Johansson *et al.* 2013). Included in the standardized work layout sheet was the worker movement chart, which described the movement pattern of the operator along with the system buffer and utilization. This activity has been done for all the operators.

Operator 1



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Aug - 2019	Manager		Process	LWR X NUT & INSPECTION

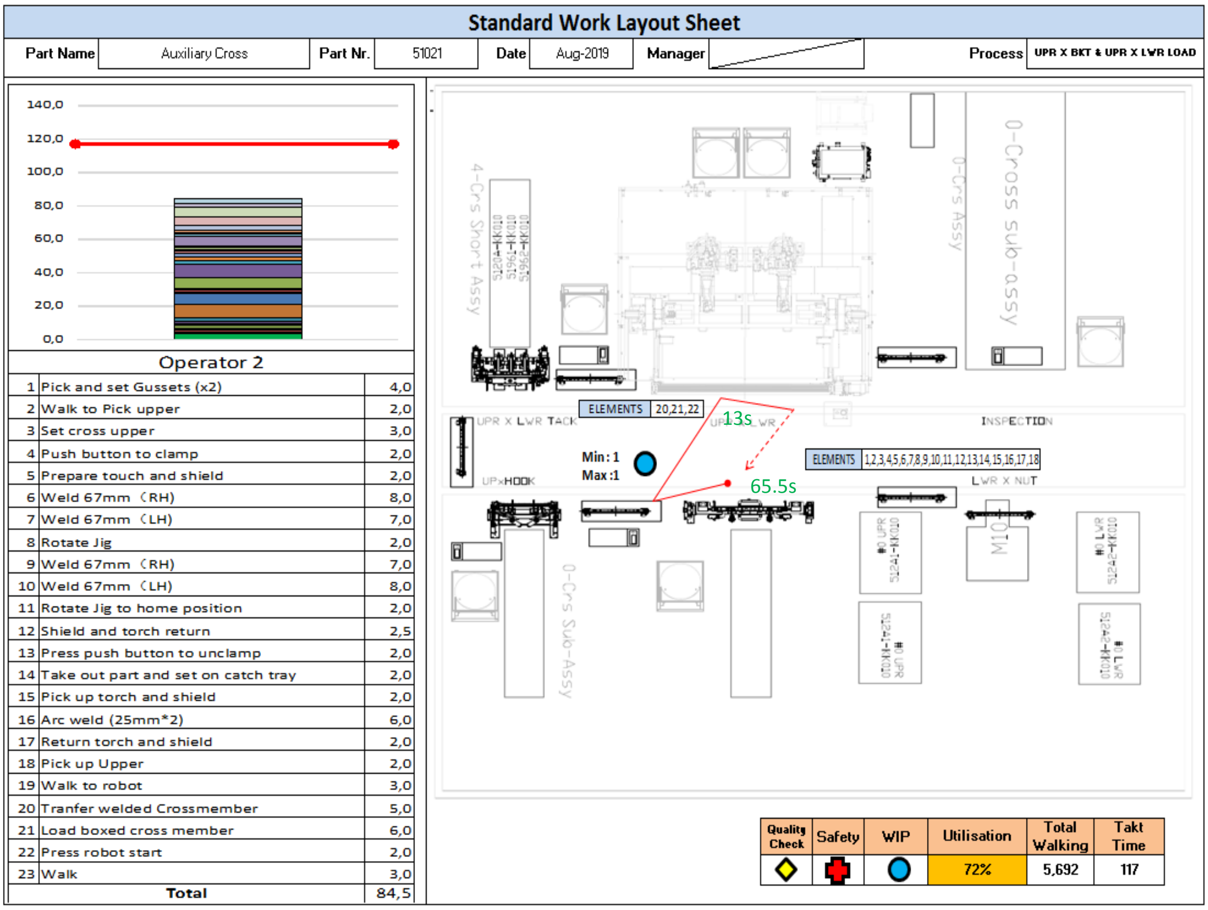
Operator 1		
1	Pick up and set Auxiliary cross on table	3,0
2	Torch and sheild preperation	3,0
3	Weld(2 x 15mm)	6,0
4	Return torch and sheild	3,0
5	Pick up marker	1,0
6	Weld inspection(2 x 15mm)	3,0
7	Rotate part	1,0
8	Inspection (1,030mm welds)	10,3
9	Rotate part	1,0
10	Return marker	1,0
11	Pick up Nut gauge	1,0
12	Inspection (10 Nuts)	18,0
13	Return nut gauge and load Auxiliary cross on	3,0
14	Walk to Lwr Nut stage	2,0
15	Pick up Upper Auxiliary Cross	5,0
16	Nut weld set	1,0
17	Nut weld (*6 Nuts)	18,0
18	Pick Up marker	1,0
19	Inspect *6 nuts	3,0
20	Return marker	1,0
21	Take out part and transfer	3,0
	Total	88,3

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◇	✚	●	75%	2,5m	117

Figure 20: Standard Work Layout Sheet - Operator 1. Adapted from Fin (2017)

According to Figure 20, Operator 1 had a multi-stage process which is illustrated by the movement diagram. The cycle time has been broken down into its respective elements andhas been further illustrated between the two stages. It can be seen that the LWR x NUT and INSPECTION processes required 32 and 54.3 seconds respectively. In addition, the total walking distance of 2.5 metreswas noted, as well as the utilization of 75%.

Operator 2



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Aug-2019	Manager		Process	UPR X BKT & UPR X LWR LOAD

Operator 2

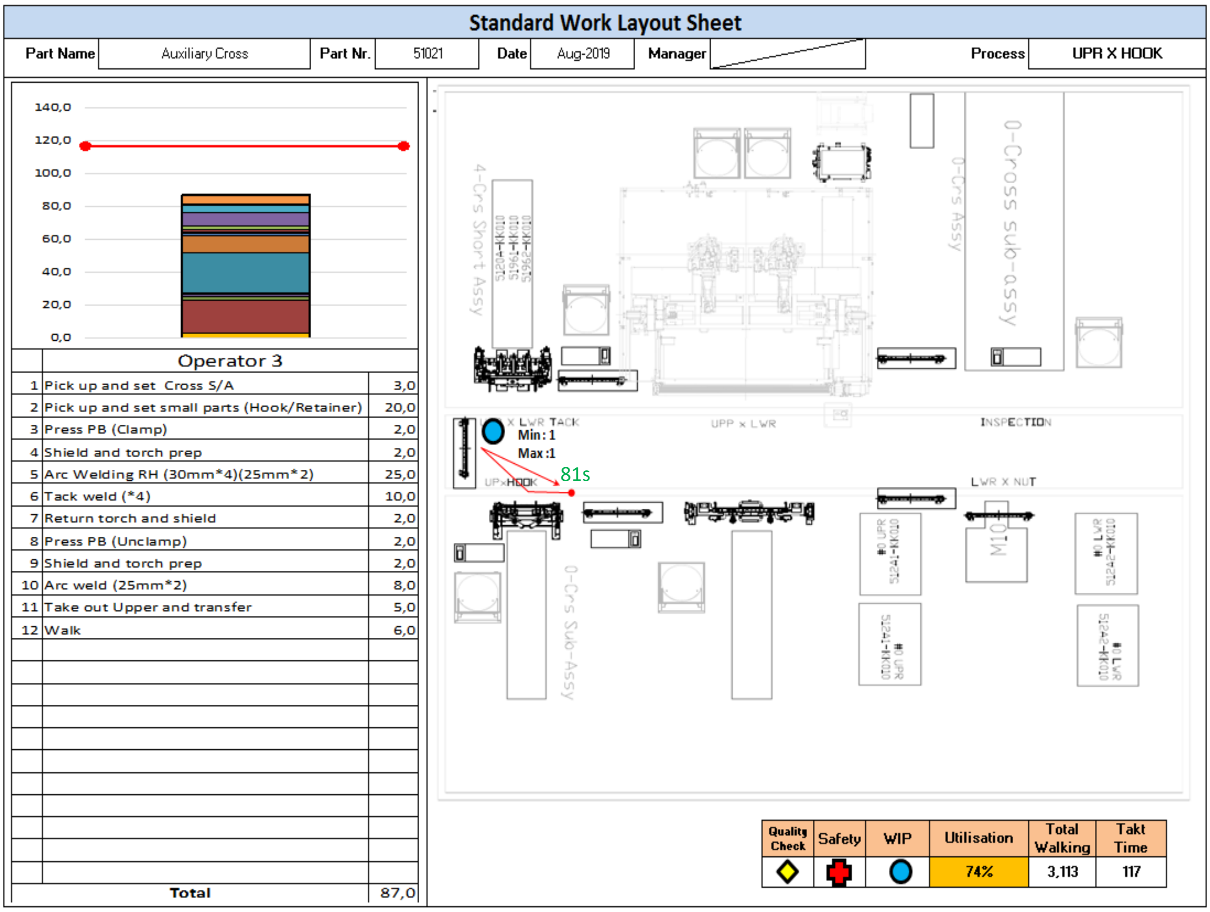
1	Pick and set Gussets (x2)	4,0
2	Walk to Pick upper	2,0
3	Set cross upper	3,0
4	Push button to clamp	2,0
5	Prepare touch and shield	2,0
6	Weld 67mm （RH)	8,0
7	Weld 67mm （LH)	7,0
8	Rotate Jig	2,0
9	Weld 67mm （RH)	7,0
10	Weld 67mm （LH)	8,0
11	Rotate Jig to home position	2,0
12	Shield and torch return	2,5
13	Press push button to unclamp	2,0
14	Take out part and set on catch tray	2,0
15	Pick up torch and shield	2,0
16	Arc weld (25mm*2)	6,0
17	Return torch and shield	2,0
18	Pick up Upper	2,0
19	Walk to robot	3,0
20	Tranfer welded Crossmember	5,0
21	Load boxed cross member	6,0
22	Press robot start	2,0
23	Walk	3,0
	Total	84,5

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◆	✚	●	72%	5,692	117

Figure 21: Standard Work Layout Sheet - Operator 2. Adapted from Fin (2017)

In Figure 21, Operator 2 also had a multi-stage process and the elements have been shown between the two stages. The UPR x BKT and UPR x LWR loading processes required 65.5 and 13 seconds respectively. Although the UPR x LWR process is an automated process, it requires manual work content in the form of part loading. The total walking distance of 5.6 metres was noted as well as the utilization of 72%.

Operator 3



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Aug-2019	Manager			Process	UPR X HOOK

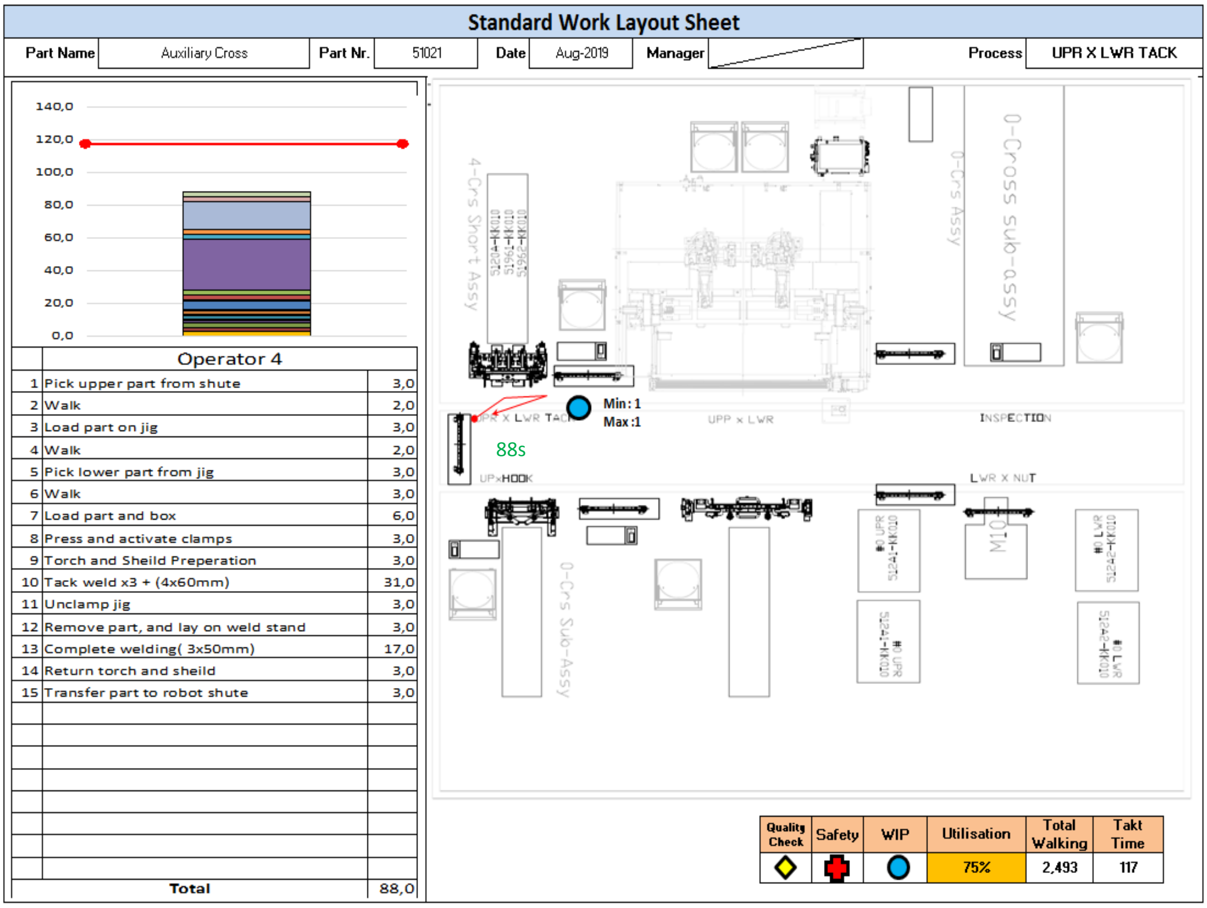
	Operator 3	
1	Pick up and set Cross S/A	3,0
2	Pick up and set small parts (Hook/Retainer)	20,0
3	Press PB (Clamp)	2,0
4	Shield and torch prep	2,0
5	Arc Welding RH (30mm*4)(25mm*2)	25,0
6	Tack weld (*4)	10,0
7	Return torch and shield	2,0
8	Press PB (Unclamp)	2,0
9	Shield and torch prep	2,0
10	Arc weld (25mm*2)	8,0
11	Take out Upper and transfer	5,0
12	Walk	6,0
	Total	87,0

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◆	✚	●	74%	3,113	117

Figure 22: Standard Work Layout Sheet - Operator 3. Adapted from Fin (2017)

Figure 22 illustrates Operator 3 with a single stage process and the individual elements. The core work required 81 seconds to be completed. The total walking distance of 3.1 metres was noted as well as the utilization of 74%.

Operator 4



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Aug-2019	Manager		Process	UPR X LWR TACK

Operator 4

1	Pick upper part from shute	3,0
2	Walk	2,0
3	Load part on jig	3,0
4	Walk	2,0
5	Pick lower part from jig	3,0
6	Walk	3,0
7	Load part and box	6,0
8	Press and activate clamps	3,0
9	Torch and Sheild Preperation	3,0
10	Tack weld x3 + (4x60mm)	31,0
11	Unclamp jig	3,0
12	Remove part, and lay on weld stand	3,0
13	Complete welding(3x50mm)	17,0
14	Return torch and sheild	3,0
15	Transfer part to robot shute	3,0
	Total	88,0

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◇	✚	●	75%	2,493	117

Figure 23: Standard Work Layout Sheet - Operator 4. Adapted from Fin (2017)

In Figure 23, Operator 4 had a single stage process as well, and the individual elements have been highlighted. The core work required 69 seconds to be completed. The total walking distance of 2.5 metres was noted as well as the utilization of 75%.

The completion of steps 1 to 3 described in the methodology has allowed the completion of the current standardized work. In addition, this section has supported the understanding and visualization of the manufacturing process. The takt time calculation and the cycle time measurement showed the current performance of the production line. The production line had an efficiency of 74.3% and demonstrated low member utilization. The information further aided the creation of the Standard Work Layout sheet and described the worker movement element by element. The element break-down assisted in the visualization of the time taken for each process. Johansson *et al.* (2013) reiterated the Japanese methodology, stating that there could be no improvement without the standardization of work. Keeping this in mind, the steps taken above would support the efficiency improvement activities going forward.

4.2.2 Measurement of Identified Services

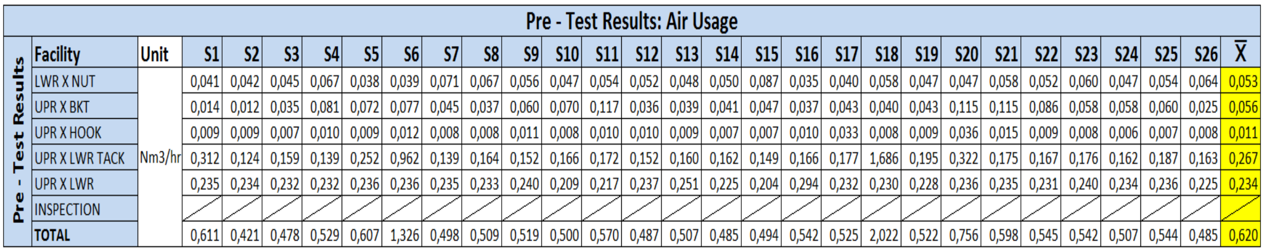
The scope of a preliminary energy measurement was to highlight the energy usage, identify wastages in major equipment processes, and set priorities for optimizing energy management(Saidur, Rahim and Hasanuzzaman 2010). In the case of this study, preliminary measurements would provide a pathway for understanding the energy consumption within the production line.

The methodology outlined air, gas, electricity and weld wire as the largest emissions emitters of the production line. The measurements were taken individually over a one-month period and the following results under each category were obtained.

4.2.2.1 Compressed air usage

In South Africa compressed air systems consumed about 9% of total energy consumption and it was therefore important to investigate the environmental impact of these systems (Gouws 2012).Here the mass flow meter was connected to each fixture within the line and monitored over 26 occurrences. The table below shows the results obtained:

Table 9: Pre-test results - air usage



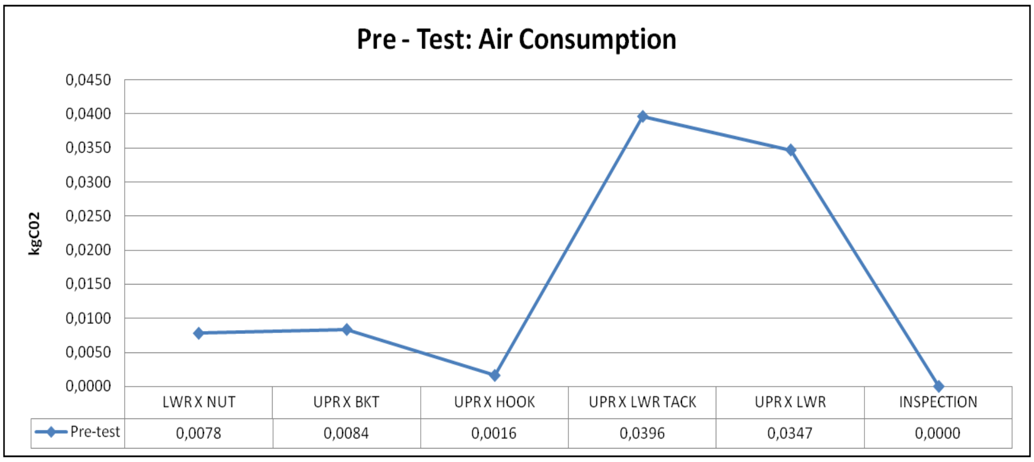
Pre - Test Results: Air Usage																													
Pre - Test Results	Facility	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	$\bar{X}$
	LWR X NUT	Nm3/hr	0,041	0,042	0,045	0,067	0,038	0,039	0,071	0,067	0,056	0,047	0,054	0,052	0,048	0,050	0,087	0,035	0,040	0,058	0,047	0,047	0,058	0,052	0,060	0,047	0,054	0,064	0,053
	UPR X BKT		0,014	0,012	0,035	0,081	0,072	0,077	0,045	0,037	0,060	0,070	0,117	0,036	0,039	0,041	0,047	0,037	0,043	0,040	0,043	0,115	0,115	0,086	0,058	0,058	0,060	0,025	0,056
	UPR X HOOK		0,009	0,009	0,007	0,010	0,009	0,012	0,008	0,008	0,011	0,008	0,010	0,010	0,009	0,007	0,007	0,010	0,033	0,008	0,009	0,036	0,015	0,009	0,008	0,006	0,007	0,008	0,011
	UPR X LWR TACK		0,312	0,124	0,159	0,139	0,252	0,962	0,139	0,164	0,152	0,166	0,172	0,152	0,160	0,162	0,149	0,166	0,177	1,686	0,195	0,322	0,175	0,167	0,176	0,162	0,187	0,163	0,267
	UPR X LWR		0,235	0,234	0,232	0,232	0,236	0,236	0,235	0,233	0,240	0,209	0,217	0,237	0,251	0,225	0,204	0,294	0,232	0,230	0,228	0,236	0,235	0,231	0,240	0,234	0,236	0,225	0,234
	INSPECTION																												
	TOTAL		0,611	0,421	0,478	0,529	0,607	1,326	0,498	0,509	0,519	0,500	0,570	0,487	0,507	0,485	0,494	0,542	0,525	2,022	0,522	0,756	0,598	0,545	0,542	0,507	0,544	0,485	0,620

Table 9 illustrates the results obtained through each fixture. The mean for each of the values has been calculated to understand the average usage per process per part. The ’Total’ row is the sum of the usages per fixture and indicates the amount of compressed air required to build one Auxiliary Cross member. The INSPECTION station has been purposely excluded, as it does not use compressed air in its process. To understand the effect on the environment, the values need to be converted to a unit of $kgC0_2$ which are outlined in Table 10:

Table 10: Compressed air emission conversion

Pre - Test Results	Facility	$\overline{X}$	Compressor Power Consumption	Unit	Electricity Emission	Unit
	LWR X NUT	0,053	0,0081	kWh	0,0078	kgC02
	UPR X BKT	0,056	0,0087	kWh	0,0084	kgC02
	UPR X HOOK	0,011	0,0017	kWh	0,0016	kgC02
	UPR X LWR TACK	0,267	0,0414	kWh	0,0396	kgC02
	UPR X LWR	0,234	0,0362	kWh	0,0347	kgC02
	INSPECTION	0,000	0,0000	kWh	0,0000	kgC02
	Total	0,620	0,0962	kWh	0,0921	kgC02

Using the TSAM compressor efficiency rate and the Eskom coal burn rate described in the methodology, a carbon emission of $0.0921\ kgC0_2$was found to have been emitted during the production of one Auxiliary Cross member. The value was further broken down into each stage and is visualized in Graph 3:



Graph 3: Pre - Test Air consumption emission

Graph 3 illustrates the emission by fixture. The highest and lowest contributors are identified as the UPR x LWR TACK stage and the UPR x HOOK stage respectively, and this forms the basis for energy management to begin.

4.2.2.2 Shielding Gas Measurement

Inert gas for arc shielding was essential in welding processes as it played a vital role in the weld pool geometry, which in turn determined the mechanical properties of the weld (Juang and Tarng 2002). However, the shielding gas was a direct environmental emission and optimizing the usage was key to reducing environmental impacts.

The table below illustrates the 26 cycles measured:

Table 11: Pre-test results - gas usage

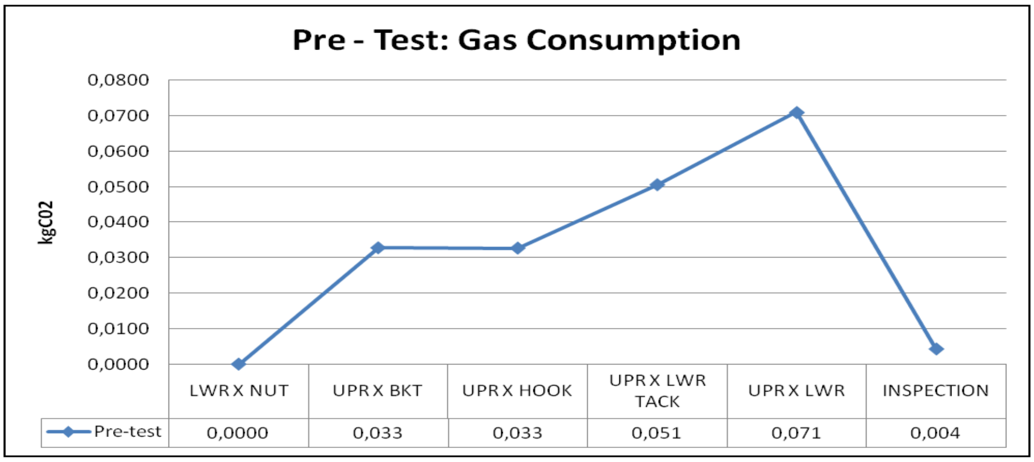
	Pre - Test Results : Shield Gas																												
	Facility	**Unit**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**	**S23**	**S24**	**S25**	**S26**	$\bar{X}$
Pre - Test Results	LWR X NUT	kg																											
	UPR X BKT		0,034	0,034	0,033	0,033	0,033	0,033	0,036	0,033	0,033	0,032	0,035	0,024	0,024	0,034	0,034	0,034	0,034	0,033	0,033	0,033	0,034	0,034	0,034	0,034	0,034	0,034	0,033
	UPR X HOOK		0,033	0,031	0,033	0,033	0,032	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,033	0,032	0,033	0,033	0,033	0,033	0,033
	UPR X LWR TACK		0,050	0,049	0,050	0,050	0,050	0,050	0,050	0,051	0,050	0,050	0,051	0,050	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,052	0,051	0,051	0,051	0,051	0,052	0,051
	UPR X LWR		0,071	0,071	0,072	0,071	0,071	0,070	0,073	0,071	0,071	0,070	0,072	0,071	0,072	0,071	0,072	0,071	0,070	0,071	0,071	0,072	0,072	0,071	0,070	0,072	0,071	0,072	0,071
	INSPECTION		0,004	0,004	0,005	0,005	0,004	0,004	0,004	0,005	0,004	0,004	0,005	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,005	0,004	0,004	0,004	0,004
	TOTAL		0,191	0,189	0,193	0,192	0,189	0,190	0,195	0,193	0,191	0,190	0,195	0,181	0,183	0,193	0,194	0,193	0,192	0,192	0,192	0,193	0,194	0,192	0,193	0,194	0,194	0,195	0,192

According to Table 11, the mean for each of the values was calculated to understand the average usage per process per part. As with the air consumption results, the sum of the mean values indicated the shielding gas consumption for the manufacturing of one Auxiliary cross member. The LWR x NUT station has been purposely excluded, as it does not use shielding gas in its process. The shielding gas is a direct emission into the environment and requires no conversion.

Table 12: Shielding Gas emission

	Facility	C02 Emission	Unit
Pre - Test Results	LWR X NUT	0,0000	kgC02
	UPR X BKT	0,033	kgC02
	UPR X HOOK	0,033	kgC02
	UPR X LWR TACK	0,051	kgC02
	UPR X LWR	0,071	kgC02
	INSPECTION	0,004	kgC02
	Total	0,192	kgC02

According to Table 12, 0.192 $kgC0_2$was used in the manufacturing of an Auxiliary cross member. Graph 4 breaks this down visually into its respective stages:



Graph 4: Pre-test - Gas consumption emission

Graph 4 provides an insight into the highest carbon emitters. UPR x LWR was the highest shielding gas consumer while the lowest were the UPR x BKT and UPR x HOOK processes.

4.2.2.3 Electricity consumption

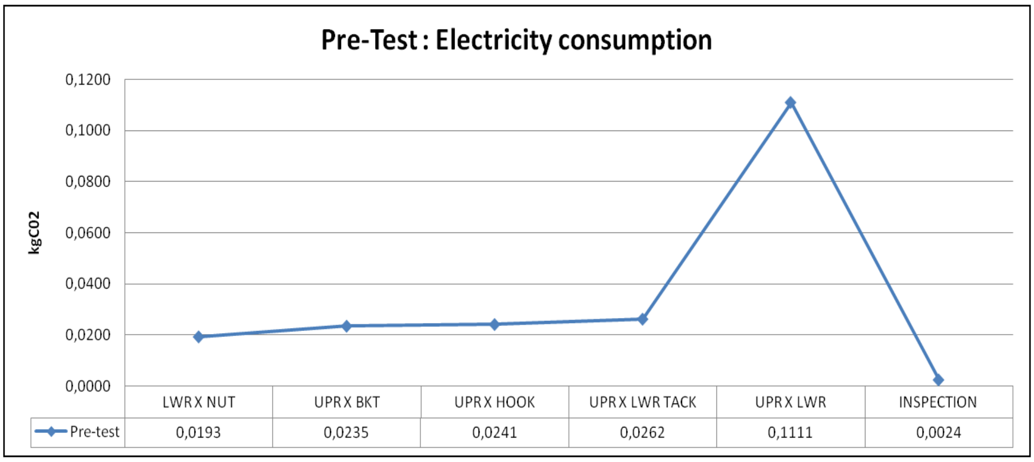
Arc welding was commonly characterized by high energy consumption and low energy efficiency, hence the focus on energy management, carbon efficiency and energy saving had become a manufacturing priority (Yan *et al.* 2017).

Attaching the power logger to each weld machine yielded the following results:

Table 13: Electricity consumption emission

Pre - Test Results	Facility	Weld machine Power Consumption	Unit	Electricity Emission	Unit
	LWR X NUT	0,0202	kWh	0,0193	kgC02
	UPR X BKT	0,0245	kWh	0,0235	kgC02
	UPR X HOOK	0,0252	kWh	0,0241	kgC02
	UPR X LWR TACK	0,0274	kWh	0,0262	kgC02
	UPR X LWR	0,1160	kWh	0,1111	kgC02
	INSPECTION	0,0025	kWh	0,0024	kgC02
	Total	0,2158	kWh	0,2067	kgC02

The electricity consumption was summarized and converted to carbon emitted. According to Table 13, the total electricity consumption during the manufacturing process amounted to $0.2067\ kgC0_2$.



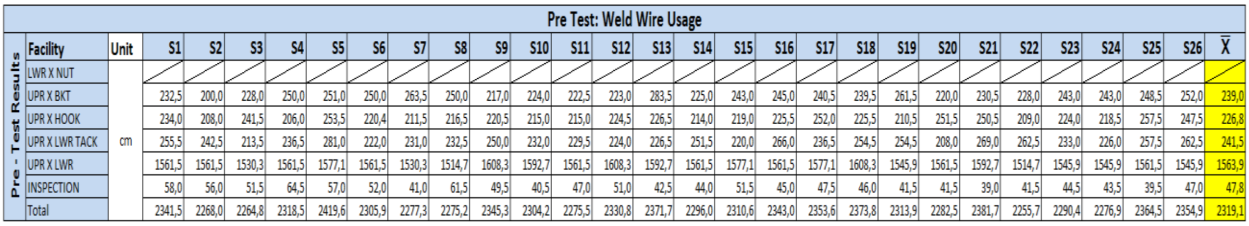
Graph 5: Pre-test - Electricity consumption emission

Graph 5 highlights the UPR x LWR station as being the largest consumer of electricity, with the lowest being the INSPECTION process. This was mainly due to the amount of welding at each process. UPR x LWR had the highest amount of welding while INSPECTION had the least amount of welding.

4.2.2.4 Weld wire consumption

Weld wire was melted by the intense heat from the arc generated by electric power and formed the joining adhesive between parts. The voltage and current outputs influenced the droplet transfer mode or wire feed rate(Kah, Suoranta and Martikainen 2013). This demonstrated that the weld settings had a direct effect on the wire consumption. The table below illustrates the wire usage based on the current electricity consumption:

Table 14: Pre-test Results - Wire usage



Pre Test: Weld Wire Usage

	Facility	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	$\bar{X}$
Pre - Test Results	LWR X NUT	cm																											
	UPR X BKT		232,5	200,0	228,0	250,0	251,0	250,0	263,5	250,0	217,0	224,0	222,5	223,0	283,5	225,0	243,0	245,0	240,5	239,5	261,5	220,0	230,5	228,0	243,0	243,0	248,5	252,0	239,0
	UPR X HOOK		234,0	208,0	241,5	206,0	253,5	220,4	211,5	216,5	220,5	215,0	215,0	224,5	226,5	214,0	219,0	225,5	252,0	225,5	210,5	251,5	250,5	209,0	224,0	218,5	257,5	247,5	226,8
	UPR X LWR TACK		255,5	242,5	213,5	236,5	281,0	222,0	231,0	232,5	250,0	232,0	229,5	224,0	226,5	251,5	220,0	266,0	236,5	254,5	254,5	208,0	269,0	262,5	233,0	226,0	257,5	262,5	241,5
	UPR X LWR		1561,5	1561,5	1530,3	1561,5	1577,1	1561,5	1530,3	1514,7	1608,3	1592,7	1561,5	1608,3	1592,7	1561,5	1577,1	1561,5	1577,1	1608,3	1545,9	1561,5	1592,7	1514,7	1545,9	1545,9	1561,5	1545,9	1563,9
	INSPECTION		58,0	56,0	51,5	64,5	57,0	52,0	41,0	61,5	49,5	40,5	47,0	51,0	42,5	44,0	51,5	45,0	47,5	46,0	41,5	41,5	39,0	41,5	44,5	43,5	39,5	47,0	47,8
	Total		2341,5	2268,0	2264,8	2318,5	2419,6	2305,9	2277,3	2275,2	2345,3	2304,2	2275,5	2330,8	2371,7	2296,0	2310,6	2343,0	2353,6	2373,8	2313,9	2282,5	2381,7	2255,7	2290,4	2276,9	2364,5	2354,9	2319,1

Table 14 illustrates the results obtained through each fixture in a unit of centimetres. The mean for each of the values was calculated to understand the average usage per process per part. The 'Total' row is the summation of the usages per fixture and indicates the amount of compressed air required to build one Auxiliary Cross member. The LWR x NUT process was purposely excluded as it did not use weld wire in its process. With this information in mind, 2319 cm or 23.19 $m$was required per Auxiliary cross member. To understand the effect on the environment, the values needed to be converted to a unit of kg.

Table 15: Wire usage conversion

Pre - Test Results	Facility	$\bar{X}$	Usage kg	Unit
	LWR X NUT			
	UPR X BKT	239,019	0,0208	kg
	UPR X HOOK	226,840	0,0197	kg
	UPR X LWR TACK	241,462	0,0210	kg
	UPR X LWR	1563,902	0,1361	kg
	INSPECTION	47,846	0,0042	kg
	Total	2319,070	0,2018	kg

According to Table 15, 2319 cm equates to 0.2018 kg. This information was critical as it could be used to estimate the number of wire drums used and disposed of as landfill waste.

Taking the volume forecast into account, the following was calculated:

Table 16: Monthly volume and wire usage

Production Volume and wire usage							
Monthly Volume	JUN	JUL	AUG	SEPT	OCT	NOV	Total
	8093	8717	9280	9199	9792	8668	53749
Wire Usage	1633	1759	1873	1856	1976	1749	10847
Drum usage	6	7	7	7	7	6	40

Tabulating the current wire usage against the forecasted volume, the wire drum usage could be forecasted. Table 16 illustrates that a total of 40 drums would be required based on a volume of 53749 production units. Each wire drum weighed 8.6 kg in packaging material resulting in 344 kg of landfill waste. This information was key to note should there be any electrical savings realised.

The measurement details outlined in the methodology section allowed for the collection of a set of baseline results. This provided an insight into energy consumption during the manufacturing process. It additionally showed the ability for the measurements to take place and to extract key information for auditing or improvement processes.

At this stage of the study, the results could not be completely interpreted, as there was minimal background data to compare them against. Throughout the study, the data representing the dependent variable was regularly analysed to monitor the effect of the independent variable.

4.2.3 Experiment Summary

The energy consumption for the standardized work done was highlighted in the chapter and formed the foundation to test the improvement theories outlined in the literature review. The next experiment, Environmental Value Stream Mapping, computed these results and displayed a holistic view of the manufacturing process.

4.3 Experiment 2 - Value Stream Mapping

The literature review has demonstrated that a Value Steam Map can be implemented to identify the environmental impacts of a process within a plant layout. The technique is commonly known as Environmental Value Stream Mapping and was developed using standard principles (Keskin, Asan and Kayakutlu 2013).

The Value Stream below illustrates the current state of the Auxiliary Cross manufacturing process:

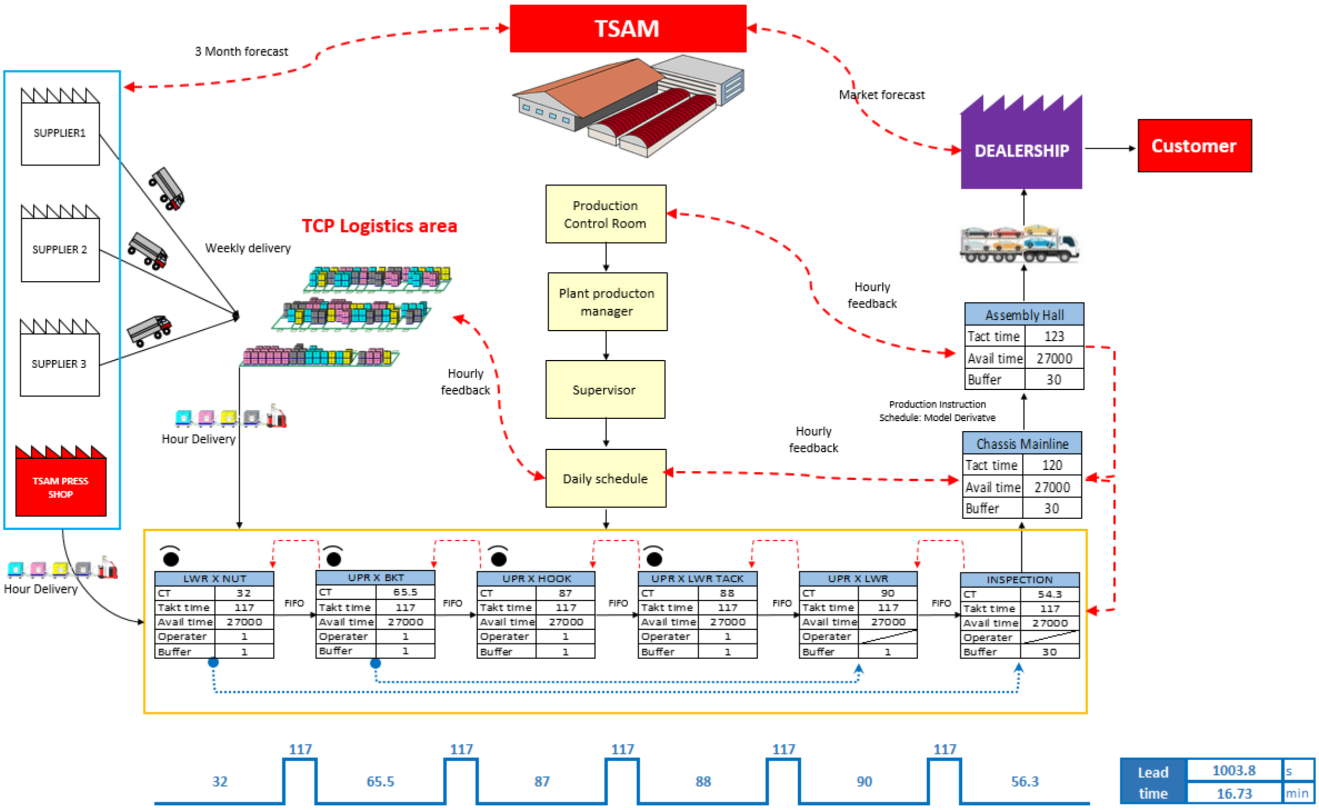


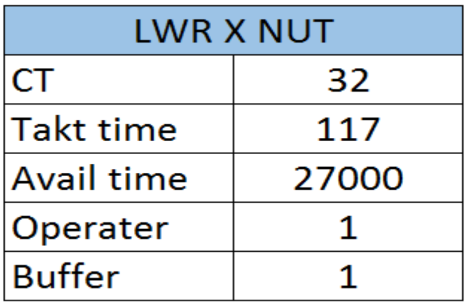
Figure 24: Auxiliary Cross member current state VSM. Adapted from Manjunath et al (2014)

The process begins with a market forecast that is acquired from the dealership sales statistics. The statistics include the monthly sales figures in terms of model and vehicle type. Based on these statistics, the production planning department projects the volumes and the production control room (PCR) develops a 3-month plan. The 3-month plan is sent to external suppliers as well as each manufacturing plant within TSAM. The plan is further broken down and the daily projected volumes are planned into the operation. This forms the first two steps outlined in the methodology as the customer requirement is computed. Using the customer requirements data, the outbound and inbound frequency of parts can additionally be determined.

The external suppliers carry out a similar procedure within their planning departments and schedule a weekly component delivery to correspond to the TSAM production call of the system. These components are delivered to the TCP logistics areas and distributed to the required assembly areas.

The TSAM press shop is an internal supplier and provides press components for weld assembly processes. The press shop is provided with a 3-month schedule as well, and the batch builds are scheduled accordingly. Due to the factories being in separate locations of the plant, the parts are delivered via a tow motor.

Table 17: Process data box



LWR X NUT	
CT	32
Takt time	117
Avail time	27000
Operater	1
Buffer	1

The manufacturing process of the Auxiliary Cross member was mapped using process data boxes. The process data boxes contained the cycle time, the number of operators available, time (in seconds)and the minimum stock required which was usually termed ‘buffer’(Manjunath *et al.* 2014). Each process was mapped as per the process sequence and flowed through to the Chassis Mainline, which supplied the Assembly Hall, where final assembly of the vehicles takes place. Steps 3 through to 6 have been carried out as mentioned in the methodology and summarized within the process box.

The objective of the Value stream was to highlight the material flow, information flow and lead time for the product being manufactured. Using this pictorial mapping technique, the inefficiencies of the system could be studied (Singh, Garg and Sharma 2011). Applying the cycle times from experiment 1, the lead-time ladder illustrated a lead-time of 16.73 minutes for the Auxiliary Cross Member, before being transported to the Mainline for chassis assembly.

Before mapping the environmental impacts, the following assumptions were considered:

a) The environmental impacts referred to the manufacturing process of the Auxiliary Cross Member.
b) The Chassis Mainline and Assembly Hall impacts were not considered for this study.
c) The Supplier impacts were not considered for this study.
d) The environmental effects from logistics and transport were not considered for this study.

Using the data obtained from Experiment 1 and the findings of the literature review, the following environmental data was mapped into the current state of the VSM:

4.3.1 EVSM Evaluation

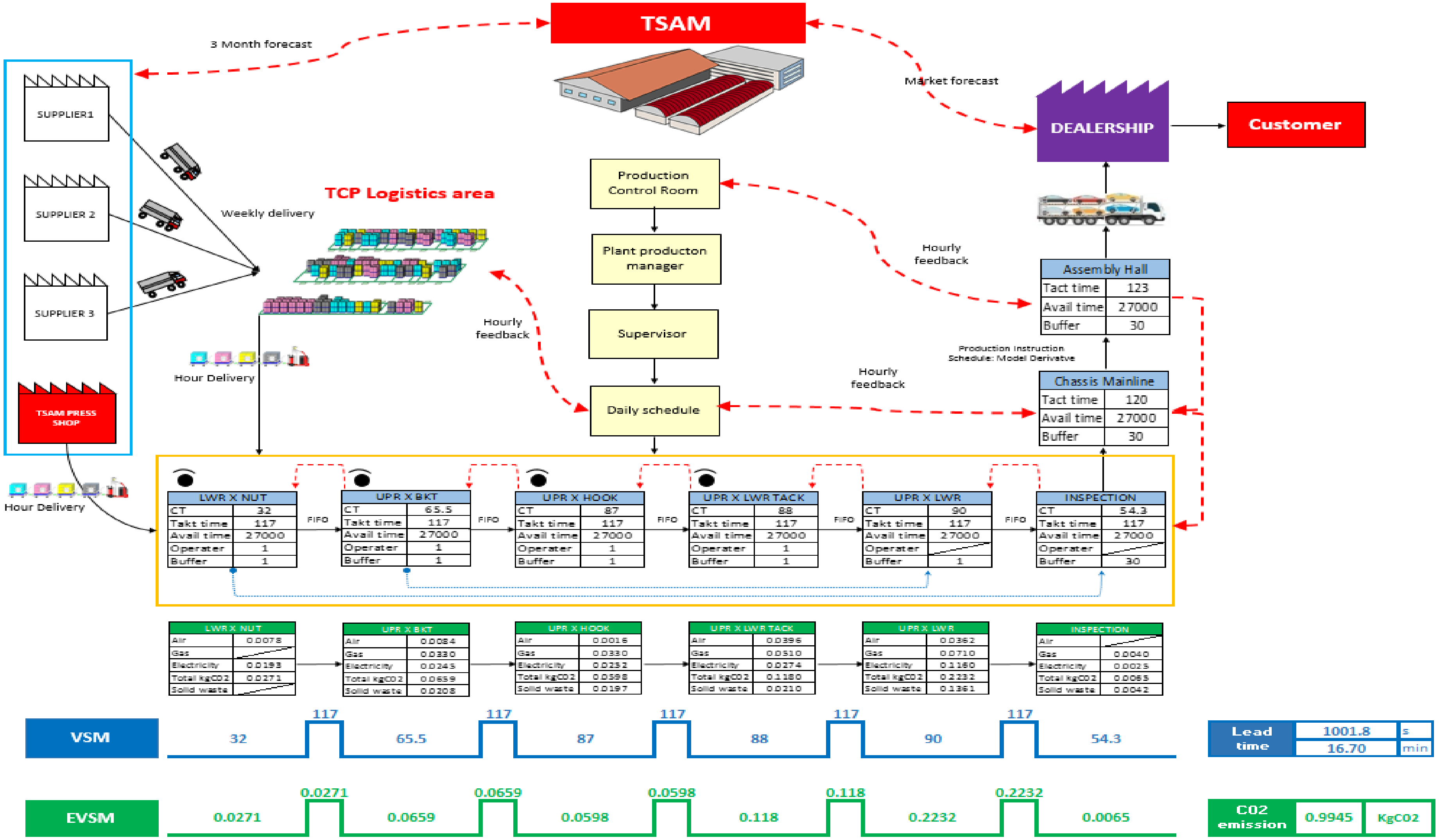
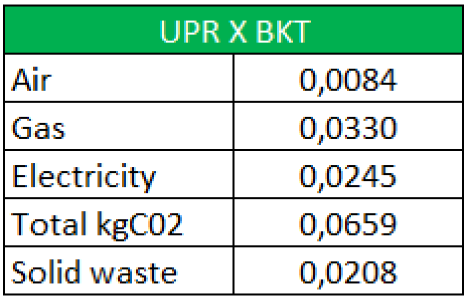


Figure 25: Auxiliary Cross member current state EVSM. Adapted from Chiarini (2014)

Figure 25 demonstrates the Environmental Value Stream Map for the current state of the process. Below the standard VSM process data boxes, the environmental data boxes have been included.

Table 18: Environmental Data Box



UPR X BKT	
Air	0,0084
Gas	0,0330
Electricity	0,0245
Total kgC02	0,0659
Solid waste	0,0208

Table 18 shows the environmental box for the UPR X BKT stage of the manufacturing process. Within this process $0.0084\, kgC0_2$ of air was used, while $0.033\, kgC0_2$ and $0.0245\, kgC0_2$ofgas and electricity respectively was used. The solid waste accounts for the weld wire packaging as it is dumped and sent to landfill sites. These figures account for a single Auxiliary Cross Member. Similarly, following the methodology of steps 7 and 8, the environmental data has been mapped for all the processes within the Auxiliary Cross Member line.

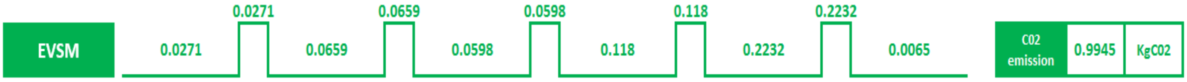


Figure 26: Carbon emissions ladder. Adapted from Verma and Sharma (2016)

Just as VSM has a lead time ladder, Figure 26 highlights a carbon emissions ladder to illustrate the accumulation of emissions throughout the process. The ladder describes the emissions from the process as well as the inventory stock, or work in progress, after the process. From this figure, it can be seen that $0.9945\, kgC0_2$ was emitted during the production of an Auxiliary Cross Member.

4.3.1 Experiment Summary

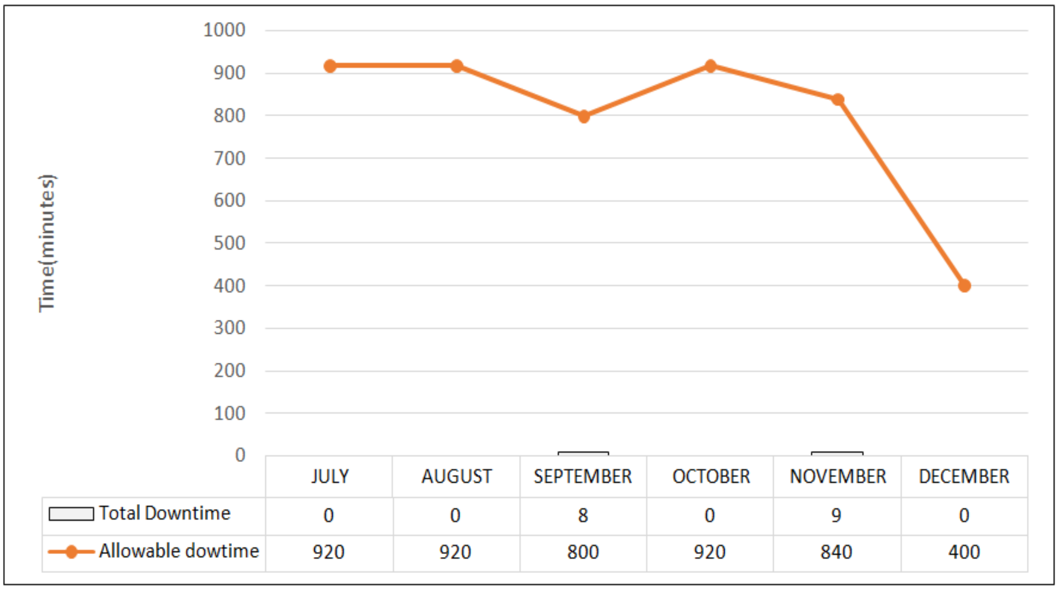
From the above results, it was evident that VSM could be used as a tool for mapping and identifying environmental impacts in a manufacturing process. The E-VSM aids in the development of a method that allows for a quick and comprehensive analysis of energy and material flows. Therefore, the theoretical finding F_1 that Value Stream Mapping can be used as a tool for mapping and identifying environmental impacts could be confirmed and accepted.

4.4. Experiment 3 - Total Productive Maintenance

A common understanding in a lean manufacturing environment was that Total Productive Maintenance (TPM) was a programme to improve productivity and quality along with increased employee morale and job satisfaction (Arunraj and Maran 2014).

TPM consisted of two important levels. The first was operator based which was also known as autonomous maintenance and included basic activities such as topping up oil levels, cleaning filters and checking various fluid and pressure levels of equipment. The second, at a more engineering level, was where maintenance staff collected and used data to continuously reduce machine downtime and improve productivity(Azizi 2015).

During a 6-month period, the maintenance downtime data was collected and analysed by the Maintenance Engineering Department. The data for the downtime collected is illustrated below:



	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
▭ Total Downtime	0	0	8	0	9	0
●— Allowable dowtime	920	920	800	920	840	400

Graph 6: Actual downtime vs. Target (6-month period)

From the data gathered, the Auxiliary Cross member incurred a total of 17 minutes of downtime in the last six months. This indicated that the line was exceptionally stable as every month was well below the allowable downtime target. This directed the maintenance team to focus more on autonomous maintenance with support from the engineering level.

TPM checks are normally done during non-production hours. This is to ensure that they do not interfere with production activity. Further to this, during non-production hours, the plant noise level is much lower, allowing one to find gas and air leaks much easier. This activity took place during non-production hours and included the following:

Table 19: Autonomous Maintenance Checks

TPM Check item	Procedure
1. Audit of weld fixture	- Verify working condition of jig - Ensure that there are no loose bolts, locating pins or jig components. - Ensure all weld fixture fail safe systems are functioning
2. Air system inspection	- Ensure correct air pressure to weld fixture (6 bar) - Ensure no leaks on pneumatic piping and cylinders - Soap solution spray test
3. Shielding gas system inspection	- Ensure the correct flow rate for gas (20 ltr/min) - Ensure no leaks on piping - Test weld part - Soap solution spray test
4. Weld parameter check	- Check weld setting is within the specified range - Test weld part

In undertaking the autonomous maintenance activity, the following results were anticipated:

Table 20: TPM vs. Anticipated Benefit

TPM Check Item	Anticipated Benefit
1. Audit of weld fixture	- Reduced potential reject rate
2. Air system inspection	- Reduction in air leakages - Reduced potential reject rate - Reduced electricity usage
3. Shielding gas system inspection	- Reduced rework rate - Reduced $C0_2$ gas leakage

4. Weld parameter check	- Reduced electricity consumption - Reduced potential reject rate - Weld wire usage reduction - solid waste

Each TPM item check was completed individually over a two and a half-month period and the results were collected.

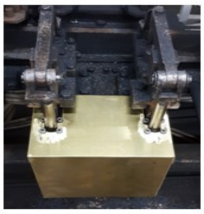
4.4.1 Compressed Air Inspection

Compressed air systems were one of the most expensive utilities to run in the manufacturing industry and could be targeted as a field full of possible energy savings (Dindorf 2012). Hence, a reduction in wasted compressed air due to inadequate maintenance and air leaks was a common technical measure that could improve energy efficiency of compressed air systems (Šešlija *et al.* 2011).

The Air System Check entailed the testing of the weld fixture to verify if any air leaks existed. This was done using the simple measures of feeling and listening for air leaks as well as verifying the pressure gauge of the fixture. In addition, a soap water solution was sprayed onto the pipes, and areas that gave off a bubble effect revealed a leak. The leaks were reported to a maintenance technician for the repair to take place.

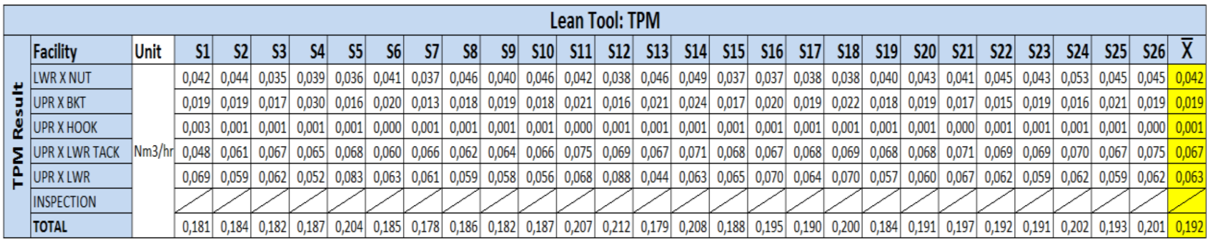
Ensuring a joint effort by production and maintenance staff supported by management was a key factor to ensure effective TPM checks and solutions were carried out(Singh, Gohil and Desai 2013). Table 20 shows the problems found and the counteractions taken by the maintenance and production team.

Table 21: Air system improvement

Date	No.	Problem	Photo	Countermeasure	Status	Photo
16.08.19	1	Weld spatter causing damage to pneumatic piping		1. Reroute piping that has exposure to weld spatter.	● complete 27.08.19	
				2. Sleeve and cover piping using specialised material that has a higher tolerance against weld spatter.		
16.08.19	2	Broken air fittings		1. Replace fittings consumable items.	● complete 27.08.19	
16.08.19	3	Leaking air cyclinders		1. Replace cylinders.	● complete 27.08.19	
				2. Manufacture brass spatter covers to protect cyclinder shafts against spatter.		

To evaluate these benefits, the mass flow meter was once again installed on the line to each fixture. The compressed air pressure supply was unchanged and only the effect of the TPM was measured. The following results shown in Table 22 were obtained:

Table 22: TPM Implementation - Air usage



Lean Tool: TPM

	Facility	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	$\bar{X}$
TPM Result	LWR X NUT	Nm3/hr	0,042	0,044	0,035	0,039	0,036	0,041	0,037	0,046	0,040	0,046	0,042	0,038	0,046	0,049	0,037	0,037	0,038	0,038	0,040	0,043	0,041	0,045	0,043	0,053	0,045	0,045	0,042
	UPR X BKT		0,019	0,019	0,017	0,030	0,016	0,020	0,013	0,018	0,019	0,018	0,021	0,016	0,021	0,024	0,017	0,020	0,019	0,022	0,018	0,019	0,017	0,015	0,019	0,016	0,021	0,019	0,019
	UPR X HOOK		0,003	0,001	0,001	0,001	0,001	0,000	0,001	0,001	0,001	0,001	0,000	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,000	0,001	0,001	0,001	0,001	0,000	0,001
	UPR X LWR TACK		0,048	0,061	0,067	0,065	0,068	0,060	0,066	0,062	0,064	0,066	0,075	0,069	0,067	0,071	0,068	0,067	0,068	0,069	0,068	0,068	0,071	0,069	0,069	0,070	0,067	0,075	0,067
	UPR X LWR		0,069	0,059	0,062	0,052	0,083	0,063	0,061	0,059	0,058	0,056	0,068	0,088	0,044	0,063	0,065	0,070	0,064	0,070	0,057	0,060	0,067	0,062	0,059	0,062	0,059	0,062	0,063
	INSPECTION																												
	TOTAL		0,181	0,184	0,182	0,187	0,204	0,185	0,178	0,186	0,182	0,187	0,207	0,212	0,179	0,208	0,188	0,195	0,190	0,200	0,184	0,191	0,197	0,192	0,191	0,202	0,193	0,201	0,192

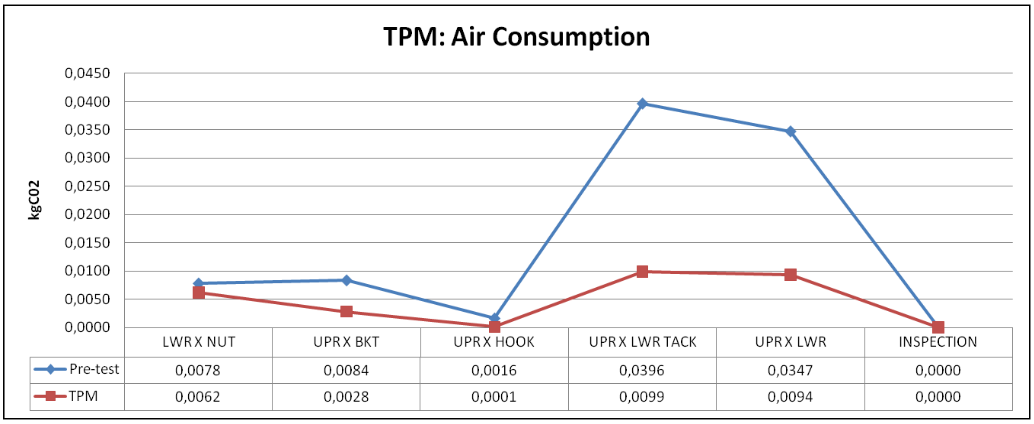
Table 22 illustrates the results for 26 samples through each fixture. The results indicated lower readings after the lean tool was applied and this was further verified by the calculated mean value. Analysing the data range for each fixture revealed that there were fewer erratic spikes across the 26 samples. This demonstrated more stable air consumption for each of the weld fixtures.

To understand the environmental impact of the exercise the readings had to be converted to $kgC0_2$. The table below describes the TCP Compressor power consumption in relation to the Eskom coal burn rate constant.

Table 23: Compressed air emission conversion

	Facility	$\overline{X}$	Compressor Power Consumption	Unit	Electricity Emission	Unit
TPM Result	LWR X NUT	0,042	0,0065	kWh	0,0062	kgC02
	UPR X BKT	0,019	0,0029	kWh	0,0028	kgC02
	UPR X HOOK	0,001	0,0001	kWh	0,0001	kgC02
	UPR X LWR TACK	0,067	0,0104	kWh	0,0099	kgC02
	UPR X LWR	0,063	0,0098	kWh	0,0094	kgC02
	INSPECTION	0,000	0,0000	kWh	0,0000	kgC02
	Total	0,192	0,0297	kWh	0,0284	kgC02

According to Table 23, after the TPM was implemented, $0.0284\ kgC0_2$ was emitted on average during the production of one Auxiliary Cross Member. Graph 8 puts this into better context by comparing the before and after conditions.



Graph 7: Before vs. After - Air Consumption

Evaluating the total system, the TPM activity achieved a saving of $0.064\ kgC0_2$ of emissions per part and that equated to a 69% reduction in emission.

4.4.2 Shielding Gas System Inspection

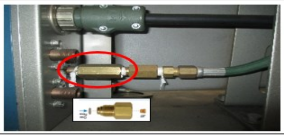
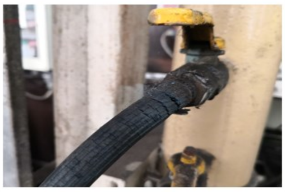
The optimization of the shielding gas flow rate within the welding environment had the potential to yield economic savings and reduce the carbon footprint (Campbell *et al.* 2013).The shielding gas system inspection involved confirms the gas level reading on the flow meter, and also checks for leaks. With any pressurized system, feeling and listening for leaks can be used as a simple check. In addition, a soap water solution can be sprayed onto the pipes, checking for the bubble effect.

Beyer et al. (2013) performed a systematic study that investigated a range of gas flow rates and weld quality. The study yielded a minimum flow rate of 12 $^{l}/_{min}$ which represented a significant cost saving and reduced environmental impact with no compromise to weld quality (Beyer *et al.* 2013).

The specific shielding gas flow rate for gas metal arc welding is typically $15 - 20\,^{l}/_{min}$, however it is often found to be adjusted to as high as 36 $^{l}/_{min}$ by welders in practice (ESAB 2011).

Table 24 highlights the problems found and the repairs and countermeasures put in place by the production and maintenance team.

Table 24: Gas system improvements

Date	No.	Problem	Photo	Countermeasure	Status	Photo
02.09.19	1	Gas flow meter reading at 30l/min		Gas flow valve turned down to 20 l/min Anti surge valve installed to prevent high flow rate	● complete 10.09.19	 
02.09.19	2	Gas leak on fitting - UPR x LWR TACK		Gas fittings replaced	● complete 10.09.19	

The reduction in flow rates and leaks should show positive signs, and the shielding gas is a direct $C0_2$ emission. The mass flow meter was installed onto the line once again and the following results were obtained as depicted in Table 25:

Table 25: TPM Implementation - Gas Consumption

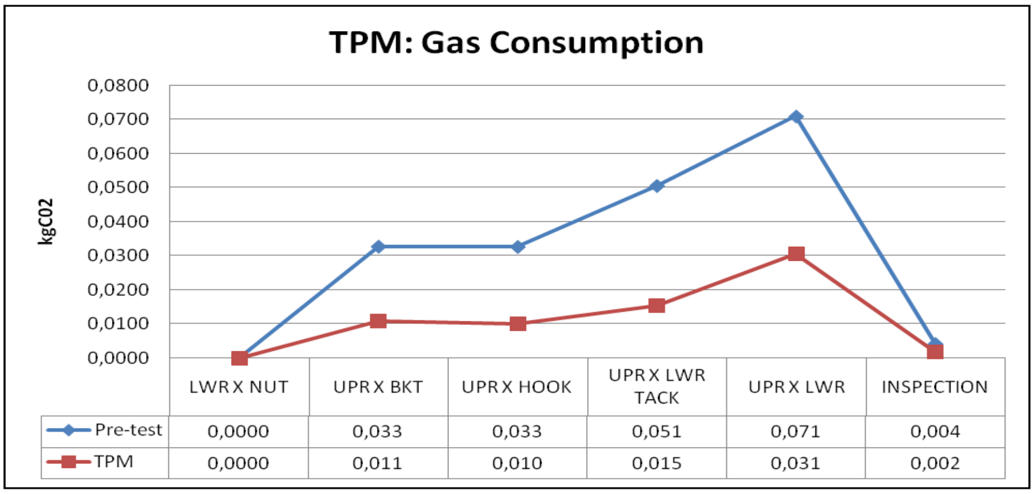
Lean Tool: TPM																													
TPM Result	Facility	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	$\bar{X}$
	LWR X NUT	kg																											
	UPR X BKT		0,011	0,011	0,011	0,011	0,011	0,011	0,008	0,014	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011
	UPR X HOOK		0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,011	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010
	UPR X LWR TACK		0,015	0,016	0,015	0,015	0,015	0,017	0,015	0,016	0,017	0,015	0,016	0,016	0,019	0,012	0,018	0,013	0,016	0,015	0,015	0,017	0,014	0,014	0,015	0,012	0,020	0,015	0,015
	UPR X LWR		0,030	0,030	0,031	0,031	0,030	0,031	0,031	0,031	0,031	0,032	0,035	0,030	0,029	0,031	0,032	0,030	0,029	0,030	0,030	0,030	0,031	0,030	0,030	0,032	0,030	0,031	0,031
	INSPECTION		0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002
	TOTAL		0,069	0,069	0,070	0,069	0,068	0,070	0,066	0,073	0,071	0,071	0,074	0,069	0,070	0,066	0,073	0,067	0,068	0,068	0,068	0,070	0,067	0,067	0,068	0,067	0,073	0,069	0,069

The usages across the 26 samples were consistent before and after the TPM implementation. During the TPM minimal leaks were found in the gas system. This explained the consistency between each sample for each fixture. The reduction in flow rate from 30 $^{l}/_{min}$ to 20 $^{l}/_{min}$ resulted in a direct drop in overall gas consumption. Table 26 and Graph 8 further highlight the reductions.

Table 26: Total gas consumption

	Facility	C02 Emission	Unit
TPM Results	LWR X NUT	0,0000	kgC02
	UPR X BKT	0,011	kgC02
	UPR X HOOK	0,010	kgC02
	UPR X LWR TACK	0,015	kgC02
	UPR X LWR	0,031	kgC02
	INSPECTION	0,002	kgC02
	Total	0,069	kgC02

On completion of the Shielding gas system check, $0.069kgC0_2$ was emitted on average during the production of one Auxiliary Cross member.



Graph 8: Before vs. After - Gas Consumption

Observing the before and after conditions, a reduction in gas usage on all facilities was detected. This reduction amounted to 64% per part manufactured.

4.4.3 Electricity Consumption - Parameter Check

Weld processes consumed a great deal of energy and were widely used in the manufacturing industry. The intense electrical arc was used as a heat source to melt metallic metals within a weld process. The welding parameters, specifically weld current, weld voltage and weld speed, affected the energy consumption to a degree (Patel and Chaudhary 2013).

Practical strategies for reducing energy consumption were vital to create eco-friendly manufacturing environments (Parslow 2012).The weld parameter check involved verifying the weld amperage and voltage settings for optimal conditions. The prescribed setting should be between 180 and 280 amps with a matching voltage range of 24 to 31 volts. Further to this, the machine could be further adjusted within the specified range to suit the welding operator’s style (ESAB 2011). In the case of this experiment, 280 amps and 31 volts would be the maximum condition for the material type and thickness used.

Through testing over the vehicle model life, TCP developed a standard setting that considered the welding operator’s speed, takt time and material type and thickness. This setting was 250 amps and 23 volts with weld bead shape, quality and penetration depth being considered. During the check, most of the manual machine settings were in the range of 280 to 310 amps with a corresponding voltage of 26 to 30 volts.

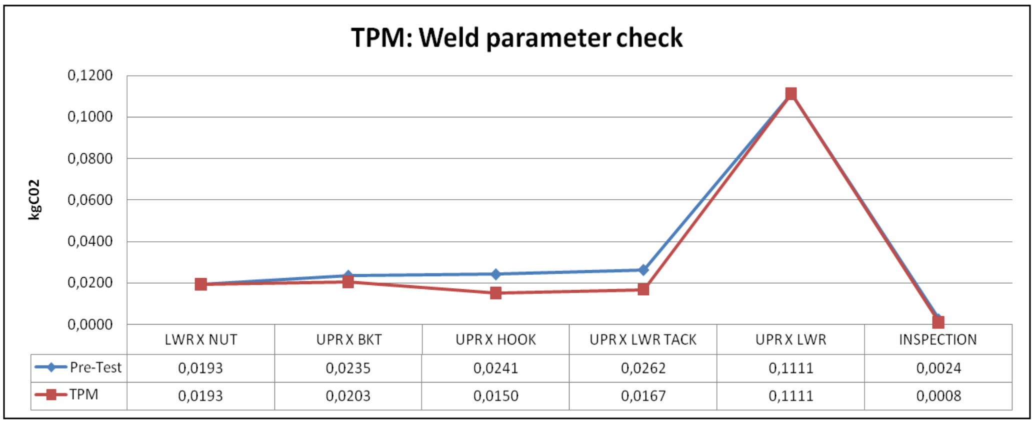
Increasing the travel weld speed while maintaining a specific voltage and current would increase weld quality until an optimum speed was reached. However, exceeding this optimum speed led to decreasing weld quality (Tewari, Gupta and Prakash 2010). Similarly, when discussing the excessively high weld settings with the operators, the general feedback was that by increasing the weld settings, a new optimal travel speed would be reached while maintaining the quality. This contributed to the seven wastes in the form of overproduction, as welding at too quick a speed would lead to excessive production and high resource usage or excessive idle time for the operators.

The parameters were lowered and with the support of the manufacturer, a digital lock was put on the machines to prevent any changes. The key codes were given to the maintenance technicians in case circumstances necessitated change. The power logger was thereafter installed back onto the line and the following results were obtained:

Table 27: Electricity emission conversion

	Facility	Weld machine Power Consumption	Unit	Electricity Emission	Unit
TPM Results	LWR X NUT	0,0202	kWh	0,0193	kgC02
	UPR X BKT	0,0212	kWh	0,0203	kgC02
	UPR X HOOK	0,0157	kWh	0,0150	kgC02
	UPR X LWR TACK	0,0175	kWh	0,0167	kgC02
	UPR X LWR	0,1160	kWh	0,1111	kgC02
	INSPECTION	0,0009	kWh	0,0008	kgC02
	Total	0,1914	kWh	0,1833	kgC02

On completion of the weld parameter check, $0.1914\ kWh$ was used for the welding operation in the manufacturing process of the Auxiliary Cross Member. This translated to $0.1833\ kgC0_2$ being emitted into the environment. Graph 9 illustrates the saving in emissions due to TPM:



	LWR X NUT	UPR X BKT	UPR X HOOK	UPR X LWR TACK	UPR X LWR	INSPECTION
Pre-Test	0,0193	0,0235	0,0241	0,0262	0,1111	0,0024
TPM	0,0193	0,0203	0,0150	0,0167	0,1111	0,0008

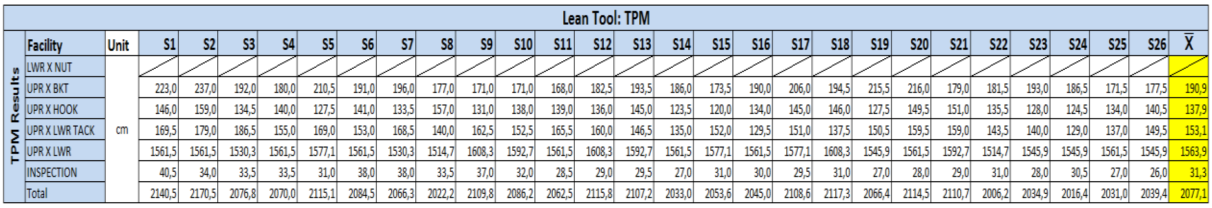
Graph 9: Before vs. After - Weld Parameter Check

The before and after results demonstrated a total saving of $0.023\ kgC0_2$ per part. The reduction in emission amounted to a total of 11.3%.

The weld parameter optimization had additional benefits based on the consumables used with the largest factor being the weld wire. Parslow (2012) found that varying the weld parameters had a direct effect on the wire/ filler usage. The specific test involved increasing the weld current, which resulted in a higher consumption of wire.

Similarly, the weld parameter check resulted in the lowering of weld settings, which should have resulted in reduced wire consumption per part. The wire usage was once again verified using the Shimpo Digital Tachometer and the following results were obtained as shown in Table 28:

Table 28: TPM - Wire Consumption



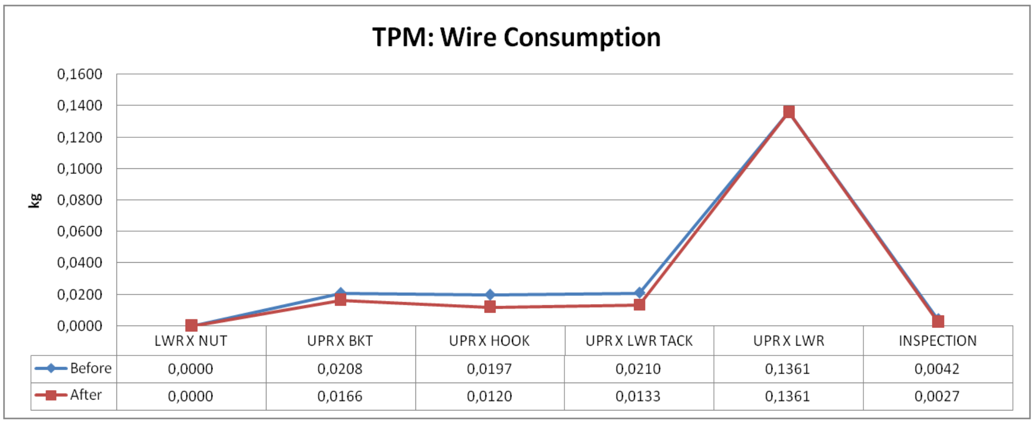
Lean Tool: TPM																														
	Facility	**Unit**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**	**S23**	**S24**	**S25**	**S26**	**$\bar{X}$**
TPM Results	LWR X NUT	cm																												
	UPR X BKT		223,0	237,0	192,0	180,0	210,5	191,0	196,0	177,0	171,0	171,0	168,0	182,5	193,5	186,0	173,5	190,0	206,0	194,5	215,5	216,0	179,0	181,5	193,0	186,5	171,5	177,5	190,9
	UPR X HOOK		146,0	159,0	134,5	140,0	127,5	141,0	133,5	157,0	131,0	138,0	139,0	136,0	145,0	123,5	120,0	134,0	145,0	146,0	127,5	149,5	151,0	135,5	128,0	124,5	134,0	140,5	137,9
	UPR X LWR TACK		169,5	179,0	186,5	155,0	169,0	153,0	168,5	140,0	162,5	152,5	165,5	160,0	146,5	135,0	152,0	129,5	151,0	137,5	150,5	159,5	159,0	143,5	140,0	129,0	137,0	149,5	153,1
	UPR X LWR		1561,5	1561,5	1530,3	1561,5	1577,1	1561,5	1530,3	1514,7	1608,3	1592,7	1561,5	1608,3	1592,7	1561,5	1577,1	1561,5	1577,1	1608,3	1545,9	1561,5	1592,7	1514,7	1545,9	1545,9	1561,5	1545,9	1563,9
	INSPECTION		40,5	34,0	33,5	33,5	31,0	38,0	38,0	33,5	37,0	32,0	28,5	29,0	29,5	27,0	31,0	30,0	29,5	31,0	27,0	28,0	29,0	31,0	28,0	30,5	27,0	26,0	31,3
	Total		2140,5	2170,5	2076,8	2070,0	2115,1	2084,5	2066,3	2022,2	2109,8	2086,2	2062,5	2115,8	2107,2	2033,0	2053,6	2045,0	2108,6	2117,3	2066,4	2114,5	2110,7	2006,2	2034,9	2016,4	2031,0	2039,4	2077,1

According to Table 28, the wire usage per stage is illustrated. The automated stage, UPR x LWR, highlighted a consistent usage of weld wire. This was mostly due to the fact that automated welding provided repeatable input parameters for more repeatable output(Chang *et al.* 2015). The welding for the remaining stages was manual and showed a larger variation between the samples. The total required length of weld wire per Auxiliary cross member was 2077.1 cm after completing the weld check. Table 29 breaks it down further:

Table 29: Wire consumption conversion

	Facility	$\bar{X}$	Usage kg	Unit
TPM Results	LWR X NUT			
	UPR X BKT	190,885	0,0166	kg
	UPR X HOOK	137,942	0,0120	kg
	UPR X LWR TACK	153,096	0,0133	kg
	UPR X LWR	1563,902	0,1361	kg
	INSPECTION	31,269	0,0027	kg
	Total	2077,1	0,1807	kg

Table 29 demonstrates the wire consumption in a kg unit. Weld wire is purchased in 250 kg drums, hence this conversion is done to better understand the drum usage. The results show that 0.1807 kg of weld wire was used to manufacture a single Auxiliary Cross Member.



	LWR X NUT	UPR X BKT	UPR X HOOK	UPR X LWR TACK	UPR X LWR	INSPECTION
Before	0,0000	0,0208	0,0197	0,0210	0,1361	0,0042
After	0,0000	0,0166	0,0120	0,0133	0,1361	0,0027

Graph 10: Before vs. After - Wire consumption

From Graph 10 it is evident that there was a reduction in weld wire usage that could be quantified as 10%. Furthermore, the graph trends for weld parameters and wire consumptions were similar, indicating that they were directly proportional to each other.

The effect of the reduction in wire usage translated to an overall reduction in landfill waste. Table 30 below shows the estimated reduction of weld wire drums utilized to make Auxiliary Cross members for the next 6 months based on the current volumes:

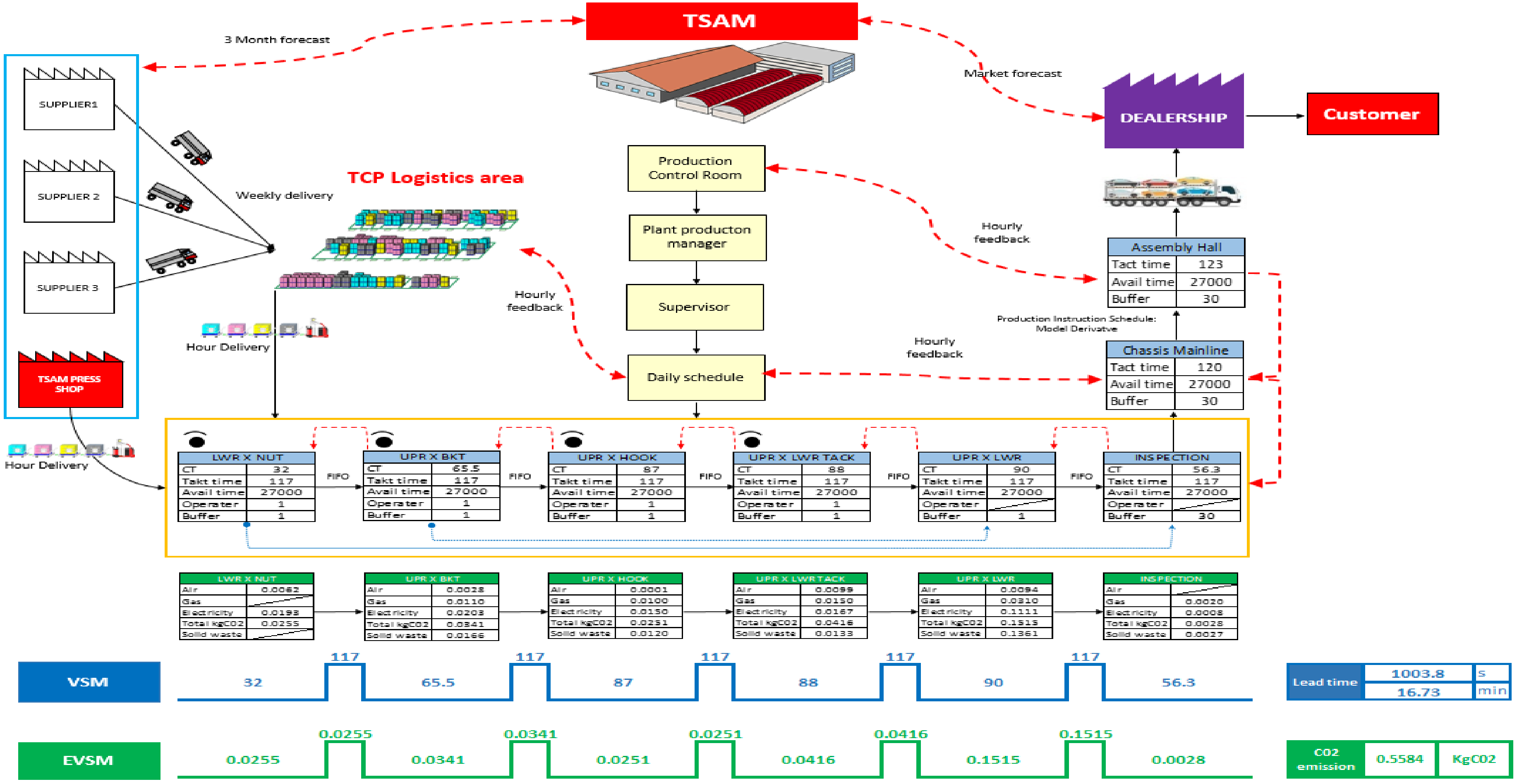
Table 30: Project volume vs. Wire usage

Production Volume and wire usage							
Monthly Volume	JUN	JUL	AUG	SEPT	OCT	NOV	Total
	8093	8717	9280	9199	9792	8668	53749
Wire Usage	1462	1575	1677	1662	1770	1566	9713
Drum usage	5	6	6	6	7	6	36

The projected volumes versus the wire usage of 'before' and 'after' are shown in Table 30. Over a 6-month period, the usage of weld wire was $9713\ kg$, a reduction of $1134\ kg$. Since the drum quantity was $250\ kg$, a calculated saving of 4.5 drums was achieved. In terms of solid waste, this amounted to a reduction of $38.7\ kg$ over a 6-month period.

4.4.4 EVSM Evaluation: TPM Activity

To better understand the effect of the TPM activity, the results were mapped once again on the E-VSM chart:



Assembly Hall	
Tact time	123
Avail time	27000
Buffer	30

Chassis Mainline	
Tact time	120
Avail time	27000
Buffer	30

	LWR X NUT	UPR X BKT	UPR X HOOK	UPR X LWR TACK	UPR X LWR	INSPECTION
CT	32	65.5	87	88	90	56.3
Takt time	117	117	117	117	117	117
Avail time	27000	27000	27000	27000	27000	27000
Operater	1	1	1	1		
Buffer	1	1	1	1	1	30

	LWR X NUT	UPR X BKT	UPR X HOOK	UPR X LWR TACK	UPR X LWR	INSPECTION
Air	0.0062	0.0028	0.0001	0.0099	0.0094	
Gas		0.0110	0.0100	0.0150	0.0310	0.0020
Electricity	0.0193	0.0203	0.0150	0.0167	0.1111	0.0008
Total kgCO2	0.0255	0.0341	0.0251	0.0416	0.1515	0.0028
Solid waste		0.0166	0.0120	0.0133	0.1361	0.0027

VSM		
	32	117
	65.5	117
	87	117
	88	117
	90	117
	56.3	

Lead time	1003.8	s
	16.73	min

EVSM	0.0255	0.0255
	0.0341	0.0341
	0.0251	0.0251
	0.0416	0.0416
	0.1515	0.1515
	0.0028	

C02 emission	0.5584	KgC02

Figure 27: E-VSM after TPM activity. Adapted from Chiarini (2014)

The E-VSM chart illustrated a total of $0.5584\ kgC0_2$ emitted for each Auxiliary Cross Member built. When compared to the initial E-VSM of $0.9945\ kgC0_2$, the TPM demonstrated a 43.8% reduction inmeasured emissions.

4.4.5 Experiment Summary

The proactive strategy of TPM allowed for the focus on processes and equipment to improve manufacturing performance. This significantly reduced equipment deterioration and failures. Thus, not only did TPM improve manufacturing performance, it also confimed the theoretical finding F_2 by reducing carbon emissions and thus affecting the environment in a positive way.

4.5 Experiment 4 - Standardized Work

Standardized work goals were the pursuit of high productivity through efficient activities. These in turn strived to obtain a production line balance among all processes to reduce production time and eliminate wastes (Fin 2017).The literature review suggested that reducing the 7 wastes would lead to environmental benefits. Standardized work was one of the most important parts of Lean Manufacturing and was key to reducing the 7 wastes (Mariz *et al.* 2012). Therefore, this experiment tests whether standardized work could reduce carbon emissions. Steps 1 to 3 outlined in the methodology have been completed in experiment 1 and have documented the current work standard. Steps 4 through to 10 will be completed now and the services re-measured to quantify the findings.

4.5.1 Stage 4 - Minimum number of operators

The manpower required for the production line can be calculated using the following formula:

$$Manpower = \frac{Total\ work\ station\ cycle\ time}{Takt\ time} \tag{4}$$

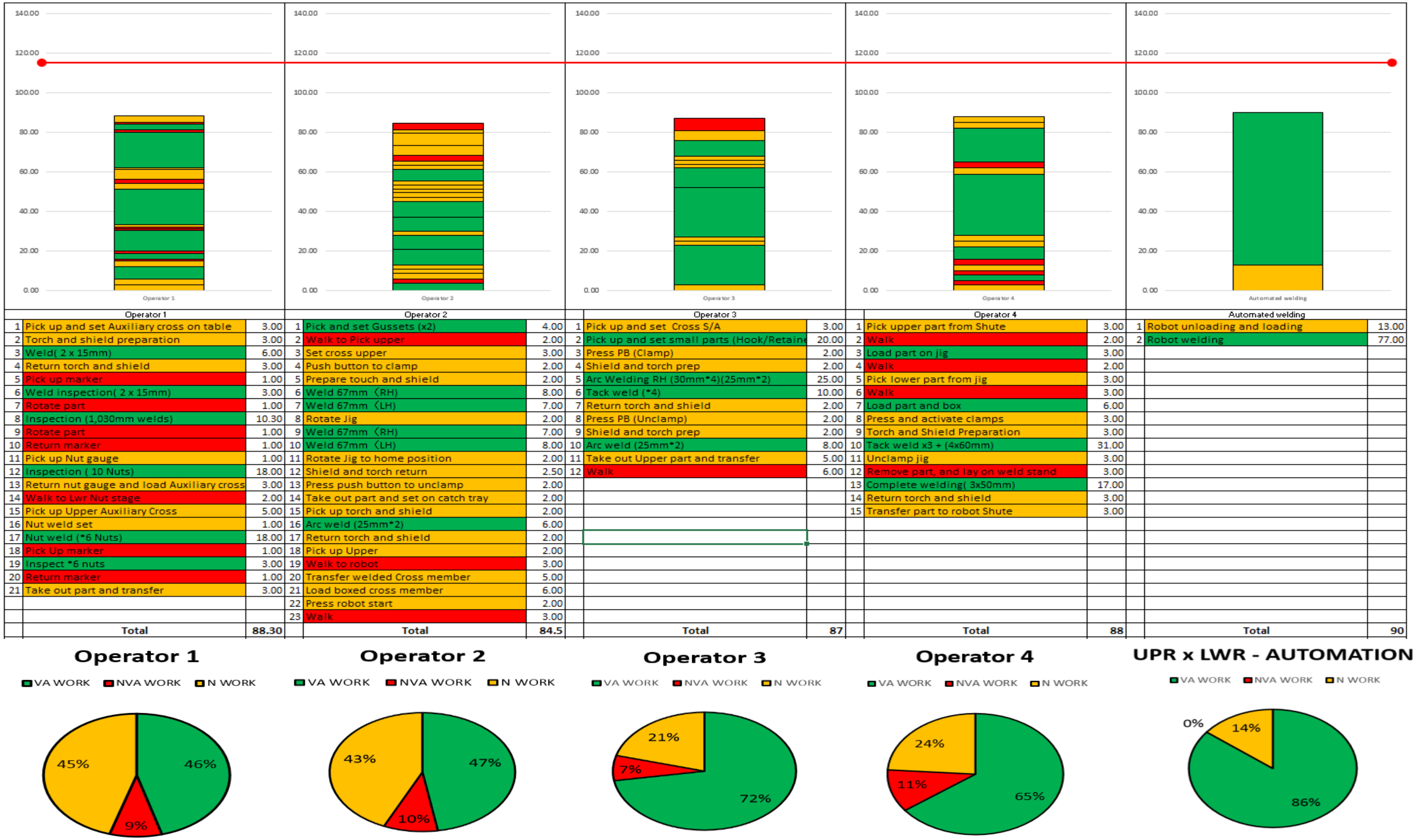
The values calculated in experiment 1 were inputted:

$$Manpower = \frac{347.8}{117} = 2.97$$

The manpower calculation equated to 2.97, which was approximately three members. This shows that only three operators were required for the production line as opposed to the current situation of four. The calculation further illustrates that there were wastes in the system and provides a deeper understanding of the 74.3% line efficiency found in experiment 1.

4.5.2 Stage 5 - Separate VA and NVA elements

The stacked graph created in experiment 1 illustrates the elements of each work cycle. To better understand the core work done in the process, the elements were categorized into Value Adding (VA) work, which changed the shape and properties of the product, Necessary (N) work, which was required but did not add value, and Non Value Adding (NVA) work that also did not add value to the product (Sabadka *et al.* 2017). This is better visualized through Figure 28.



	Operator 1	
1	🟨 Pick up and set Auxiliary cross on table	3.00
2	🟨 Torch and shield preparation	3.00
3	🟩 Weld(2 x 15mm)	6.00
4	🟨 Return torch and shield	3.00
5	🟥 Pick up marker	1.00
6	🟩 Weld inspection(2 x 15mm)	3.00
7	🟥 Rotate part	1.00
8	🟩 Inspection (1,030mm welds)	10.30
9	🟥 Rotate part	1.00
10	🟥 Return marker	1.00
11	🟨 Pick up Nut gauge	1.00
12	🟩 Inspection (10 Nuts)	18.00
13	🟨 Return nut gauge and load Auxiliary cross	3.00
14	🟥 Walk to Lwr Nut stage	2.00
15	🟨 Pick up Upper Auxiliary Cross	5.00
16	🟨 Nut weld set	1.00
17	🟩 Nut weld (*6 Nuts)	18.00
18	🟥 Pick Up marker	1.00
19	🟩 Inspect *6 nuts	3.00
20	🟥 Return marker	1.00
21	🟨 Take out part and transfer	3.00
	Total	**88.30**

	Operator 2	
1	🟩 Pick and set Gussets (x2)	4.00
2	🟥 Walk to Pick upper	2.00
3	🟨 Set cross upper	3.00
4	🟨 Push button to clamp	2.00
5	🟨 Prepare touch and shield	2.00
6	🟩 Weld 67mm （RH)	8.00
7	🟩 Weld 67mm （LH)	7.00
8	🟨 Rotate Jig	2.00
9	🟩 Weld 67mm （RH)	7.00
10	🟩 Weld 67mm （LH)	8.00
11	🟨 Rotate Jig to home position	2.00
12	🟨 Shield and torch return	2.50
13	🟨 Press push button to unclamp	2.00
14	🟨 Take out part and set on catch tray	2.00
15	🟨 Pick up torch and shield	2.00
16	🟩 Arc weld (25mm*2)	6.00
17	🟨 Return torch and shield	2.00
18	🟨 Pick up Upper	2.00
19	🟥 Walk to robot	3.00
20	🟨 Transfer welded Cross member	5.00
21	🟨 Load boxed cross member	6.00
22	🟨 Press robot start	2.00
23	🟥 Walk	3.00
	Total	**84.5**

	Operator 3	
1	🟨 Pick up and set Cross S/A	3.00
2	🟩 Pick up and set small parts (Hook/Retaine	20.00
3	🟨 Press PB (Clamp)	2.00
4	🟨 Shield and torch prep	2.00
5	🟩 Arc Welding RH (30mm*4)(25mm*2)	25.00
6	🟩 Tack weld (*4)	10.00
7	🟨 Return torch and shield	2.00
8	🟨 Press PB (Unclamp)	2.00
9	🟨 Shield and torch prep	2.00
10	🟩 Arc weld (25mm*2)	8.00
11	🟨 Take out Upper part and transfer	5.00
12	🟥 Walk	6.00
	Total	**87**

	Operator 4	
1	🟨 Pick upper part from Shute	3.00
2	🟥 Walk	2.00
3	🟩 Load part on jig	3.00
4	🟥 Walk	2.00
5	🟨 Pick lower part from jig	3.00
6	🟥 Walk	3.00
7	🟩 Load part and box	6.00
8	🟨 Press and activate clamps	3.00
9	🟨 Torch and Shield Preparation	3.00
10	🟩 Tack weld x3 + (4x60mm)	31.00
11	🟨 Unclamp jig	3.00
12	🟥 Remove part, and lay on weld stand	3.00
13	🟩 Complete welding(3x50mm)	17.00
14	🟨 Return torch and shield	3.00
15	🟨 Transfer part to robot Shute	3.00
	Total	**88**

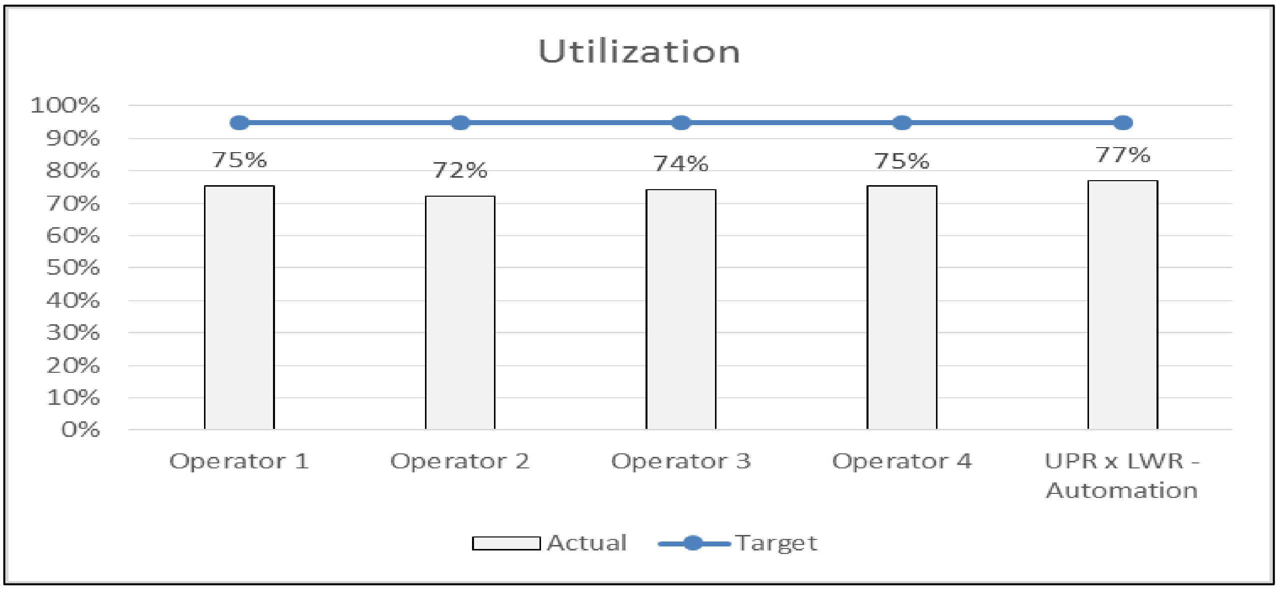
	Automated welding	
1	🟨 Robot unloading and loading	13.00
2	🟩 Robot welding	77.00
	Total	**90**

Figure 28: VA and NVA Work. Adapted from Sabadka et al. (2017)

Operators 1 and 2 had the lowest VA work content at 46% and 47% respectively. However, they also had a high N work content that needed to be done for the process to continue. Operators 3 and 4 had a high VA work content as most of the processes to change the product shape were done in these stages. The automated welding stage had a maximum VA work content and measured 86%. It should also be mentioned that this process had the most welding content of 980mm. The NVA work was minimal and constituted a maximum of 11% of total processes. The low NVA work content highlighted that there were minimal wastes within the line and the process was focused on VA and N work. Understanding the work content along with the line efficiency and operator utilization provided fundamental knowledge to balance and level operations.

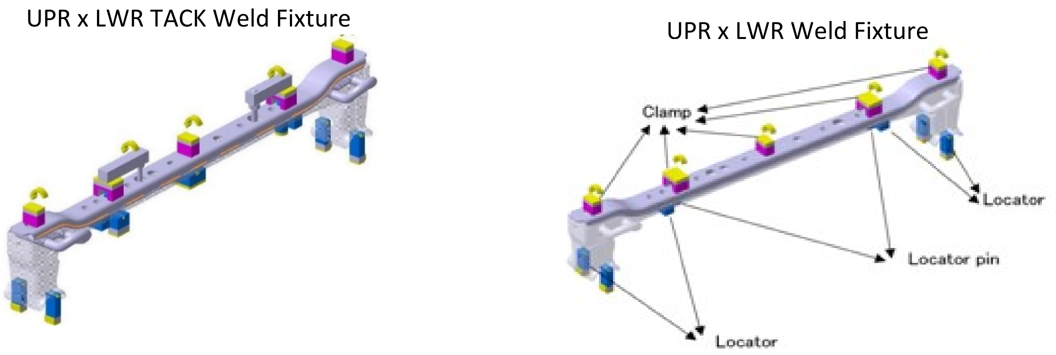
4.5.3 Stage 6 - Line Balance

Line balancing could enhance the process efficiency by minimizing workstations and work cycles, in turn maximizing work load and improving flexibility among work stations (Sagwekar, Rajhans and Hans undated).The line efficiency calculated in step 2 of experiment 1 amounted to 74.3%. Boosting efficiency involved reducing Non-Value Adding activities, element reallocation and reduction of manpower(Hasta 2019). Due to the low Non-Value adding work content found in Step 5, the line balance would focus on work reallocation.



Graph 11: Utilization of Operators and Equipment

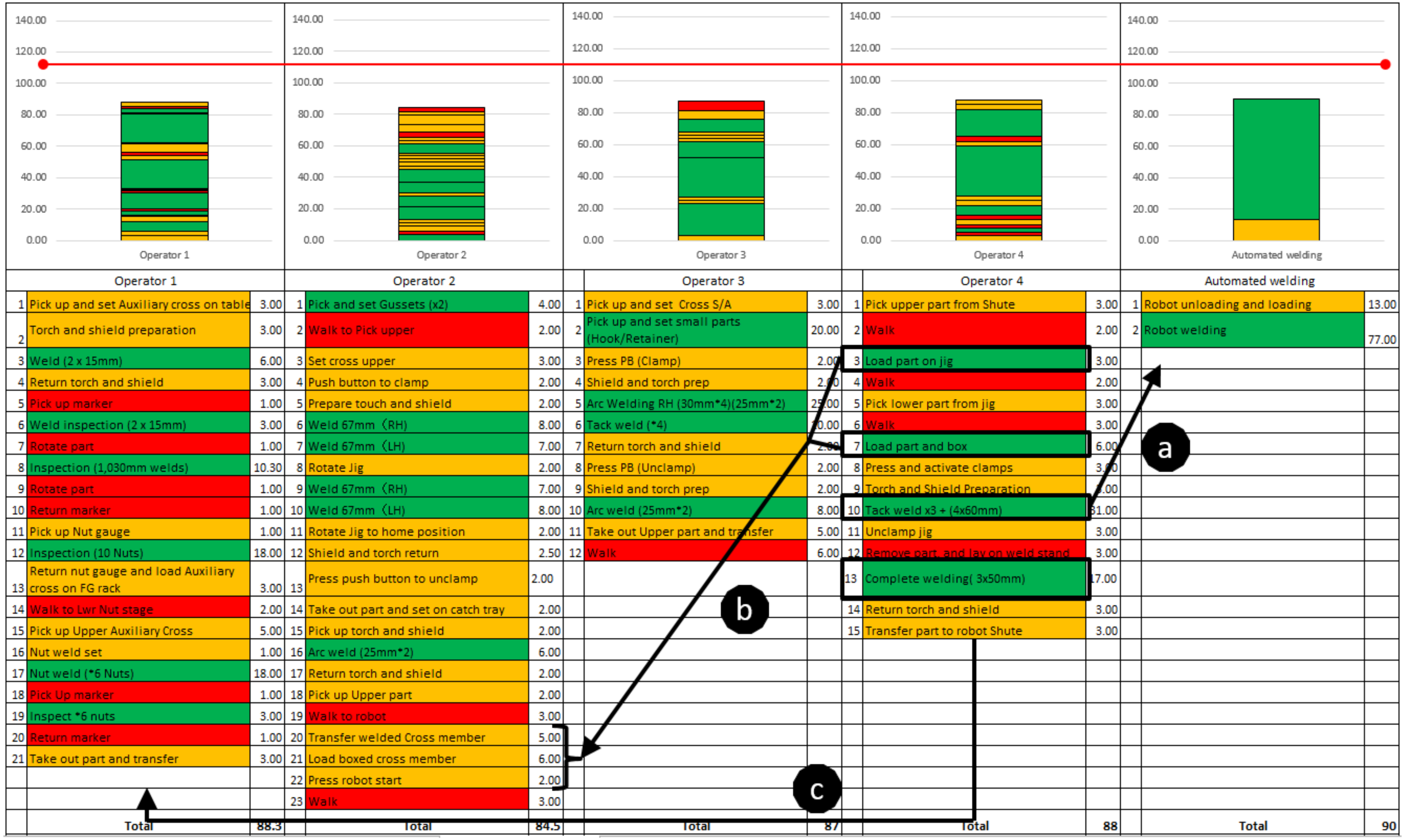
Analysing the utilization of equipment and operators, it could be clearly seen that the UPR x LWR automated process was only 77% utilized. This indicated that the equipment had excess capacity and could take on some manual weld content.


UPR x LWR TACK Weld Fixture

UPR x LWR Weld Fixture

Figure 29: Weld Fixture Schematic (Tanaka 2014)

Further studies of the line highlighted that the UPR x LWR Tack process and UPR x LWR process weld fixtures were similar and shared the same mechanical characteristics. With this information, the line balancing activity could be carried out:



	Operator 1	
1	Pick up and set Auxiliary cross on table	3.00
2	Torch and shield preparation	3.00
3	Weld (2 x 15mm)	6.00
4	Return torch and shield	3.00
5	Pick up marker	1.00
6	Weld inspection (2 x 15mm)	3.00
7	Rotate part	1.00
8	Inspection (1,030mm welds)	10.30
9	Rotate part	1.00
10	Return marker	1.00
11	Pick up Nut gauge	1.00
12	Inspection (10 Nuts)	18.00
13	Return nut gauge and load Auxiliary cross on FG rack	3.00
14	Walk to Lwr Nut stage	2.00
15	Pick up Upper Auxiliary Cross	5.00
16	Nut weld set	1.00
17	Nut weld (*6 Nuts)	18.00
18	Pick Up marker	1.00
19	Inspect *6 nuts	3.00
20	Return marker	1.00
21	Take out part and transfer	3.00
	Total	88.3

	Operator 2	
1	Pick and set Gussets (x2)	4.00
2	Walk to Pick upper	2.00
3	Set cross upper	3.00
4	Push button to clamp	2.00
5	Prepare touch and shield	2.00
6	Weld 67mm （RH)	8.00
7	Weld 67mm （LH)	7.00
8	Rotate Jig	2.00
9	Weld 67mm （RH)	7.00
10	Weld 67mm （LH)	8.00
11	Rotate Jig to home position	2.00
12	Shield and torch return	2.50
13	Press push button to unclamp	2.00
14	Take out part and set on catch tray	2.00
15	Pick up torch and shield	2.00
16	Arc weld (25mm*2)	6.00
17	Return torch and shield	2.00
18	Pick up Upper part	2.00
19	Walk to robot	3.00
20	Transfer welded Cross member	5.00
21	Load boxed cross member	6.00
22	Press robot start	2.00
23	Walk	3.00
	Total	84.5

	Operator 3	
1	Pick up and set Cross S/A	3.00
2	Pick up and set small parts (Hook/Retainer)	20.00
3	Press PB (Clamp)	2.00
4	Shield and torch prep	2.00
5	Arc Welding RH (30mm*4)(25mm*2)	25.00
6	Tack weld (*4)	10.00
7	Return torch and shield	2.00
8	Press PB (Unclamp)	2.00
9	Shield and torch prep	2.00
10	Arc weld (25mm*2)	8.00
11	Take out Upper part and transfer	5.00
12	Walk	6.00
	Total	87

	Operator 4	
1	Pick upper part from Shute	3.00
2	Walk	2.00
3	Load part on jig	3.00
4	Walk	2.00
5	Pick lower part from jig	3.00
6	Walk	3.00
7	Load part and box	6.00
8	Press and activate clamps	3.00
9	Torch and Shield Preparation	.00
10	Tack weld x3 + (4x60mm)	31.00
11	Unclamp jig	3.00
12	Remove part, and lay on weld stand	3.00
13	Complete welding(3x50mm)	17.00
14	Return torch and shield	3.00
15	Transfer part to robot Shute	3.00
	Total	88

	Automated welding	
1	Robot unloading and loading	13.00
2	Robot welding	77.00
	Total	90

Figure 30: Reallocation of work element. Adapted from Sabadka et al. (2017)

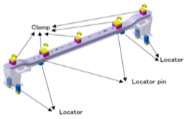
Figure 30 illustrates the reallocation of work elements within the production line. The following was noted:

a. Element 13, a Value Adding activity, could move to the UPR x LWR process to improve operator utilization. Both elements 10 and 13 could be moved to the automated process; however, after some investigation, it was found that only element 13 would work due to welding programme constraints.
b. Since the majority of the welding was going to be completed in the UPR x LWR process, the next step included moving the loading element to Operator 2. Operator 2 currently only loaded the robot and thus had enough capacity to take on elements 3 and 7 from Operator 4. Hence, the boxing process could be included in Operator 2’s cyclic work.
c. The remaining weld process of Operator 4, element 13, could be moved to Operator 1 and completed in the inspection stage. Operator 1 had ample capacity to take on the additional process.

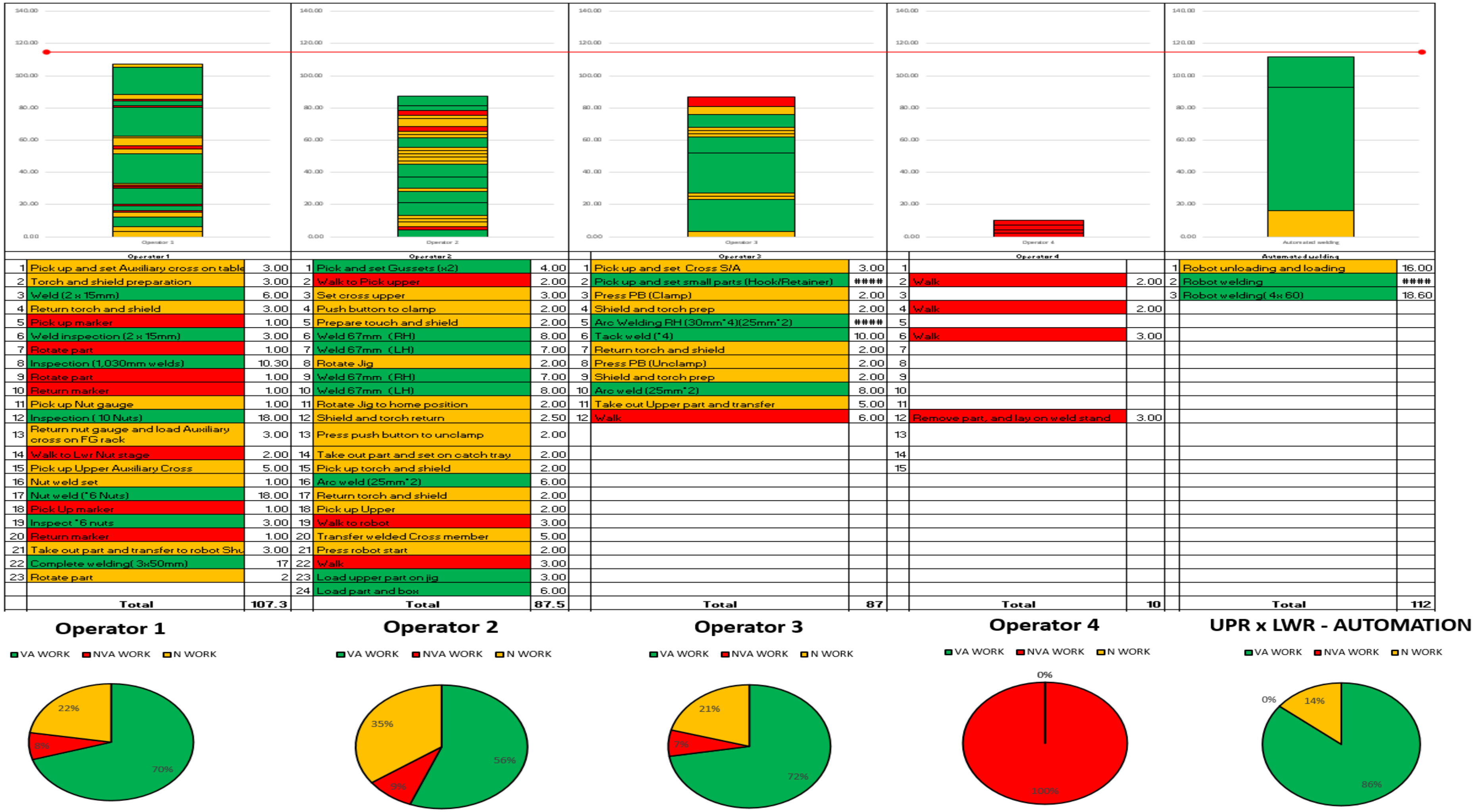
The Value-adding steps were removed from Operator 4 and redistributed through the line in an effort to achieve an improved Operator and Equipment utilization and line efficiency.

Thereafter the proposal was discussed with the line management, engineering and maintenance teams to understand which improvement activities needed to take place to ensure the line balancing could be achieved. The table below demonstrates the improvement activities carried out:

Table 31: Standardized Work improvements

Date	No.	Problem	Photo	Countermeasure	Status	Photo
02.11.19	1	Operator does not have space to put part after welding Case nuts to lower panel		Install additional Brackets on UPR x LWR exit rack to supply lower panel sub-assembly directly to the UPR x LWR process.	●	
02.11.19	2	Location pins not high enough to allow for assembly in the UPR x LWR process		Modify pins to same specification as UPR x LWR Tack station.	●	
02.11.19	3	Incorrect assembly condition in robot with potential to cause rejects.		Install position sensors on clamp cylinders to serve as a pokeyoke.	●	

The final image of the line will only include 3 Operators and is broken down as shown in Figure31:



	Operator 1	
1	Pick up and set Auxiliary cross on table	3.00
2	Torch and shield preparation	3.00
3	Weld (2 x 15mm)	6.00
4	Return torch and shield	3.00
5	Pick up marker	1.00
6	Weld inspection (2 x 15mm)	3.00
7	Rotate part	1.00
8	Inspection (1,030mm welds)	10.30
9	Rotate part	1.00
10	Return marker	1.00
11	Pick up Nut gauge	1.00
12	Inspection (10 Nuts)	18.00
13	Return nut gauge and load Auxiliary cross on FG rack	3.00
14	Walk to Lwr Nut stage	2.00
15	Pick up Upper Auxiliary Cross	5.00
16	Nut weld set	1.00
17	Nut weld (*6 Nuts)	18.00
18	Pick Up marker	1.00
19	Inspect *6 nuts	3.00
20	Return marker	1.00
21	Take out part and transfer to robot Shu	3.00
22	Complete welding(3x50mm)	17
23	Rotate part	2
	Total	**107.3**

	Operator 2	
1	Pick and set Gussets (x2)	4.00
2	Walk to Pick upper	2.00
3	Set cross upper	3.00
4	Push button to clamp	2.00
5	Prepare touch and shield	2.00
6	Weld 67mm (RH)	8.00
7	Weld 67mm (LH)	7.00
8	Rotate Jig	2.00
9	Weld 67mm (RH)	7.00
10	Weld 67mm (LH)	8.00
11	Rotate Jig to home position	2.00
12	Shield and torch return	2.50
13	Press push button to unclamp	2.00
14	Take out part and set on catch tray	2.00
15	Pick up torch and shield	2.00
16	Arc weld (25mm*2)	6.00
17	Return torch and shield	2.00
18	Pick up Upper	2.00
19	Walk to robot	3.00
20	Transfer welded Cross member	5.00
21	Press robot start	2.00
22	Walk	3.00
23	Load upper part on jig	3.00
24	Load part and box	6.00
	Total	**87.5**

	Operator 3	
1	Pick up and set Cross S/A	3.00
2	Pick up and set small parts (Hook/Retainer)	####
3	Press PB (Clamp)	2.00
4	Shield and torch prep	2.00
5	Arc Welding RH (30mm*4)(25mm*2)	####
6	Tack weld (*4)	10.00
7	Return torch and shield	2.00
8	Press PB (Unclamp)	2.00
9	Shield and torch prep	2.00
10	Arc weld (25mm*2)	8.00
11	Take out Upper part and transfer	5.00
12	Walk	6.00
	Total	**87**

	Operator 4	
1		
2	Walk	2.00
3		
4	Walk	2.00
5		
6	Walk	3.00
7		
8		
9		
10		
11		
12	Remove part, and lay on weld stand	3.00
13		
14		
15		
	Total	**10**

	Automated welding	
1	Robot unloading and loading	16.00
2	Robot welding	####
3	Robot welding(4x 60)	18.60
	Total	**112**

Figure 31: Line balance and reallocation of elements. Adapted from Sabadka et al. (2017)

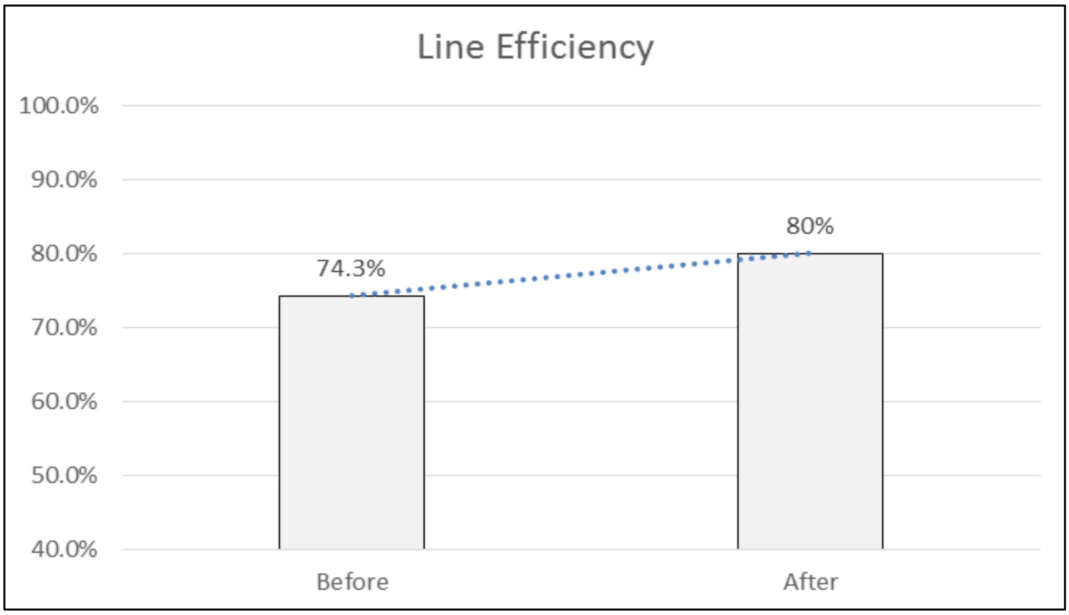
The VA work content for operators 1 and 2 has been increased by 24% and 9% respectively, simultaneously decreasing their N work proportionally. There was no addition or removal of work content to the work cycle of Operator 3. Operator 4 has had all VA work content reallocated. The N work has become redundant and the only work element left is NVA work. Hence, Operator 4's work cycle has been removed from the process. Although the UPR x LWR automated stage took on another welding element, the VA work content percentage remained the same due to the increased time for the loading element.

4.5.4 Stage 7 – Efficiency Calculation

$$Efficiency = \frac{Total\ work\ station\ cycle\ time}{Takt\ time\ \times\ no.of\ operators} \times 100 \qquad (3)$$

$$Efficiency = \frac{281.8}{351} \times 100$$

$$Efficiency = 80\%$$



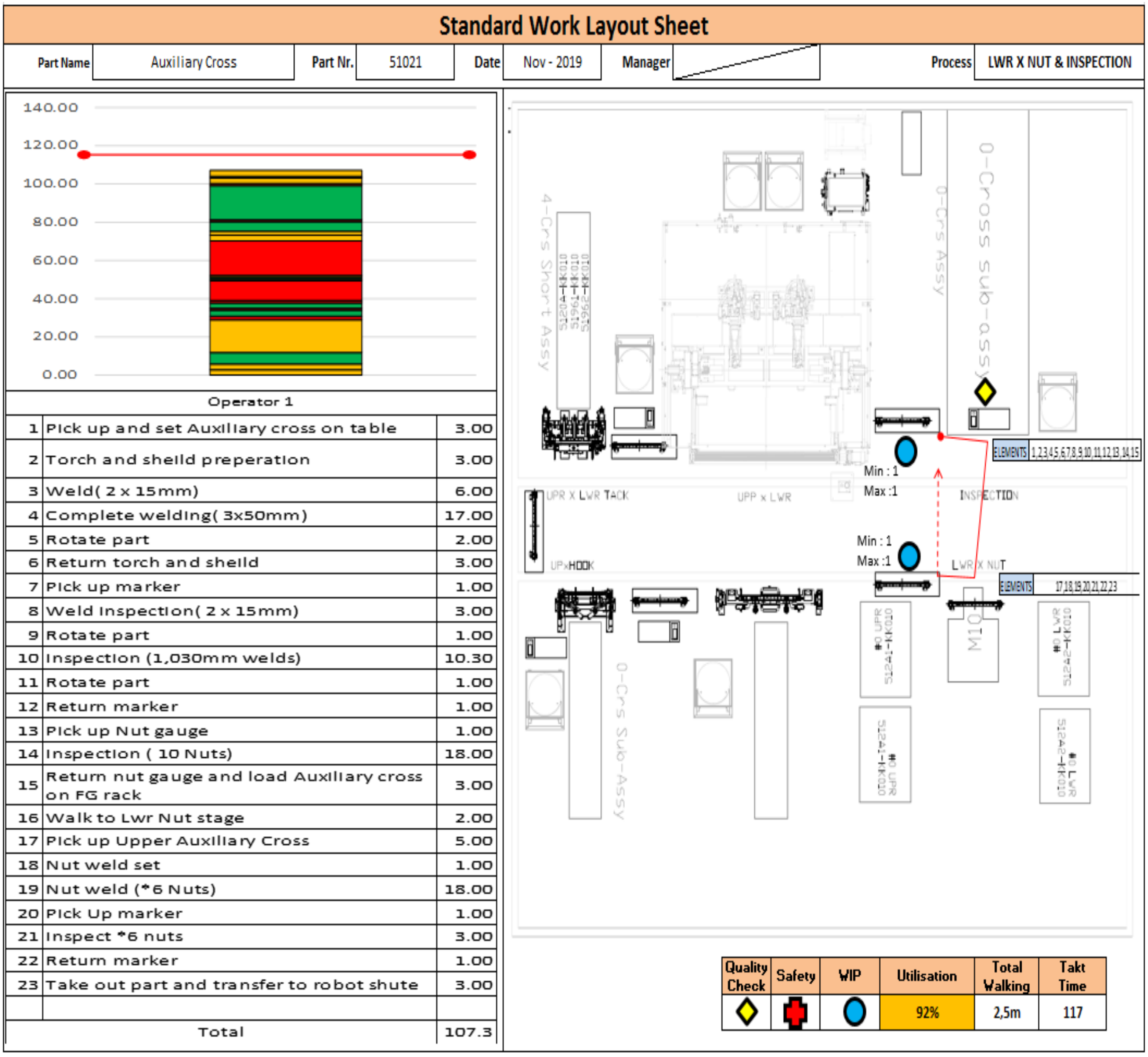
Graph 12: Line Efficiency Improvement

The reallocation of VA adding activities and reduction in manpower has boosted the line efficiency from 74.3% to 80%, resulting in a 5.7% improvement.

4.5.5 Stage 8 – Standard Work Layout Sheet

The standard work layout sheets were amended to indicate the new elements of the three operators and visualize the workflow:

Operator 1



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Nov - 2019	Manager		Process	LWR X NUT & INSPECTION

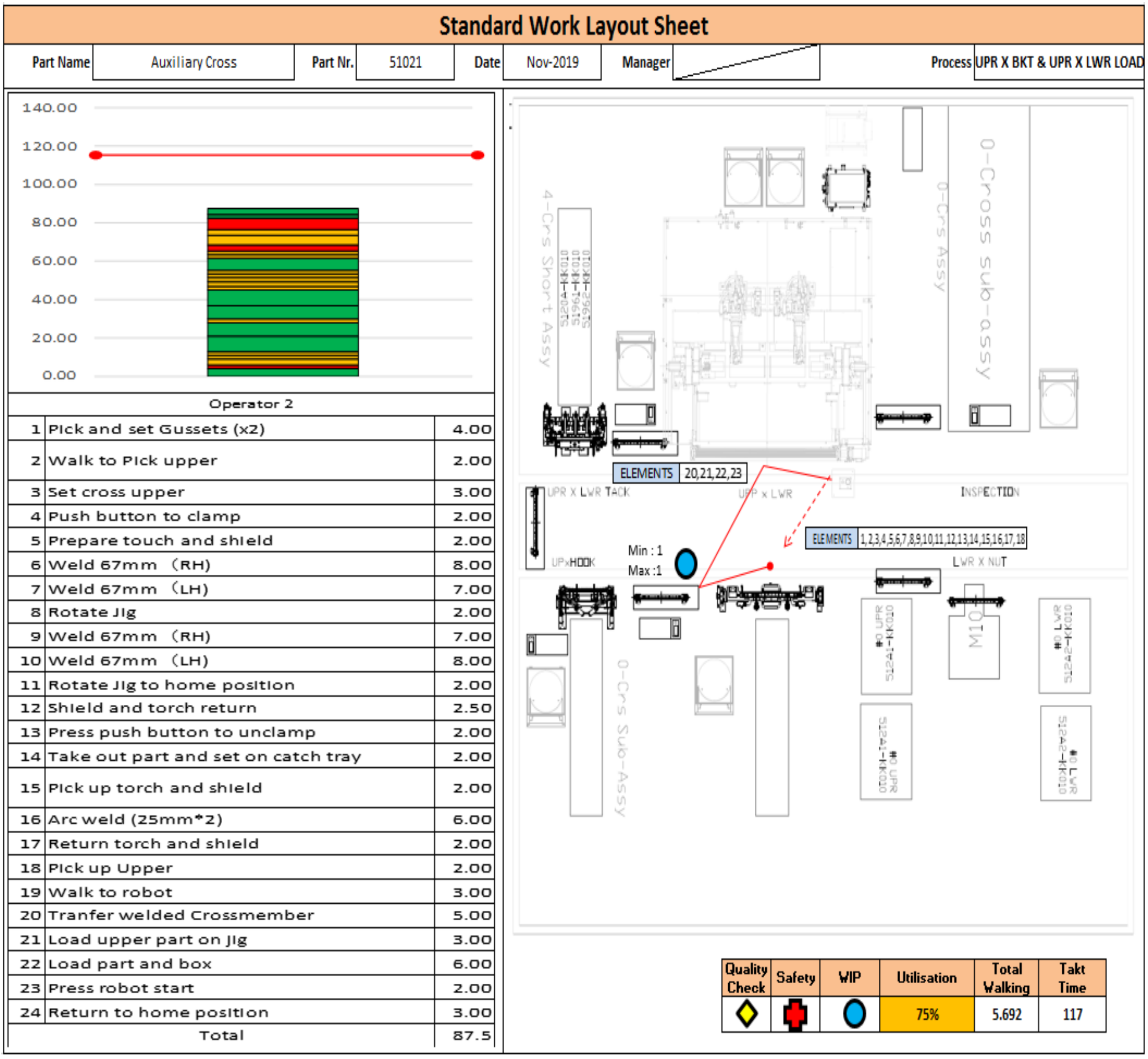
1	Pick up and set Auxiliary cross on table	3.00
2	Torch and sheild preperation	3.00
3	Weld(2 x 15mm)	6.00
4	Complete welding(3x50mm)	17.00
5	Rotate part	2.00
6	Return torch and sheild	3.00
7	Pick up marker	1.00
8	Weld inspection(2 x 15mm)	3.00
9	Rotate part	1.00
10	Inspection (1,030mm welds)	10.30
11	Rotate part	1.00
12	Return marker	1.00
13	Pick up Nut gauge	1.00
14	Inspection (10 Nuts)	18.00
15	Return nut gauge and load Auxiliary cross on FG rack	3.00
16	Walk to Lwr Nut stage	2.00
17	Pick up Upper Auxiliary Cross	5.00
18	Nut weld set	1.00
19	Nut weld (*6 Nuts)	18.00
20	Pick Up marker	1.00
21	Inspect *6 nuts	3.00
22	Return marker	1.00
23	Take out part and transfer to robot shute	3.00
	Total	107.3

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◆	✚	●	92%	2,5m	117

Figure 32: Operator 1 Standard Work Layout Sheet. Adapted from Fin (2017)

Operator 1’s cycle time has been increased to 107.3 seconds, equating to an improved utilization figure of 92%. This was largely due to the increased work content at the INSPECTION process with element 4 as the new addition. The cyclic movement and buffer conditions have remained the same to ensure minimal change points. Minimizing the change points has allowed for an easier and shortened training period.

Operator 2



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Nov-2019	Manager		Process	UPR X BKT & UPR X LWR LOAD

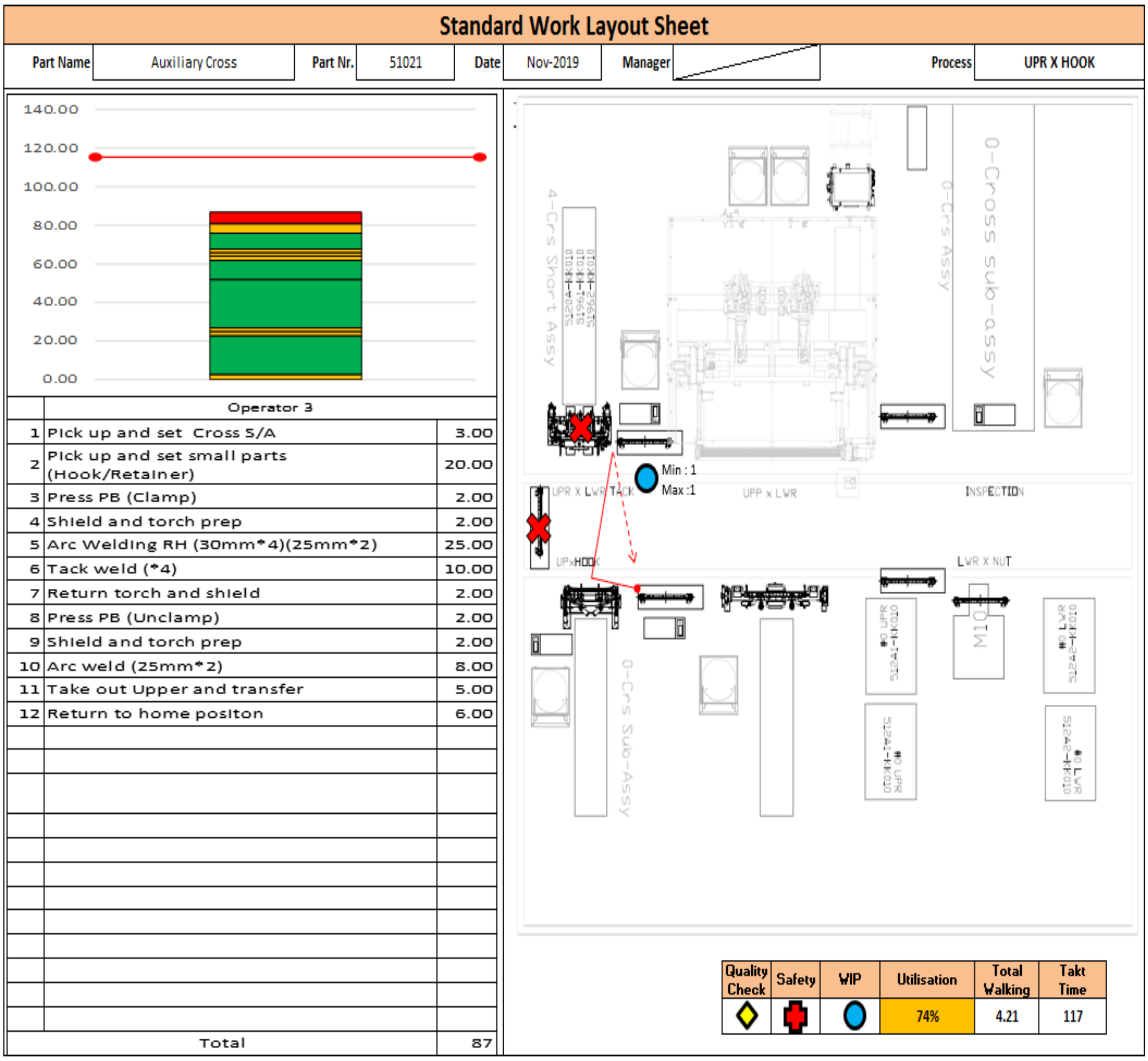
1	Pick and set Gussets (x2)	4.00
2	Walk to Pick upper	2.00
3	Set cross upper	3.00
4	Push button to clamp	2.00
5	Prepare touch and shield	2.00
6	Weld 67mm (RH)	8.00
7	Weld 67mm (LH)	7.00
8	Rotate Jig	2.00
9	Weld 67mm (RH)	7.00
10	Weld 67mm (LH)	8.00
11	Rotate Jig to home position	2.00
12	Shield and torch return	2.50
13	Press push button to unclamp	2.00
14	Take out part and set on catch tray	2.00
15	Pick up torch and shield	2.00
16	Arc weld (25mm*2)	6.00
17	Return torch and shield	2.00
18	Pick up Upper	2.00
19	Walk to robot	3.00
20	Tranfer welded Crossmember	5.00
21	Load upper part on Jig	3.00
22	Load part and box	6.00
23	Press robot start	2.00
24	Return to home position	3.00
	Total	87.5

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◆	✚	●	75%	5.692	117

Figure 33: Operator 2 Standard Work Layout Sheet. Adapted from Fin (2017)

Operator 2 has had a cycle time increase of only 3 seconds, resulting in a utilization of 75%. The additional elements of UPR x LWR loading have contributed to the increase in cycle time. The cyclic work has remained the same, allowing for minimal change points.

Operator 3



Standard Work Layout Sheet

Part Name	Auxiliary Cross	Part Nr.	51021	Date	Nov-2019	Manager		Process	UPR X HOOK

	Operator 3	
1	Pick up and set Cross S/A	3.00
2	Pick up and set small parts (Hook/Retainer)	20.00
3	Press PB (Clamp)	2.00
4	Shield and torch prep	2.00
5	Arc Welding RH (30mm*4)(25mm*2)	25.00
6	Tack weld (*4)	10.00
7	Return torch and shield	2.00
8	Press PB (Unclamp)	2.00
9	Shield and torch prep	2.00
10	Arc weld (25mm*2)	8.00
11	Take out Upper and transfer	5.00
12	Return to home positon	6.00
	Total	87

Quality Check	Safety	WIP	Utilisation	Total Walking	Takt Time
◇	✚	●	74%	4.21	117

Figure 34: Operator 3 Standard Work Layout Sheet. Adapted from Fin (2017)

Operator 3 has undergone no major change in work content, except for the fact that the buffer drop-off point has changed. This has had an inconsequential effect on the cyclic work and no effect on the cycle time; hence the utilization remains the same.

4.5.6 Stage 9 – Training and Implementation

The successful implementation of lean thinking depended on the training after the introduction of standardized work (Sihombing, Rassiah and Chidambaram 2011). Thus, a meeting with the line management and operators of the control group was held to propose the improvement of the activity as well as the method objectives. The importance of performing all the activities in the established order was explained as a requirement to achieve a more efficient process while understanding the effect on carbon emissions.

The standard work layout sheet was used as the training material and the additional information on the sheet was explained. Due to the minimal number of change points for this improvement activity, the line management and operators readily accepted the proposed revised method. Operator 4 did not take part in the trial activity but supported the collection of data. Once the trial began, the study of the carbon emissions could continue.

4.5.7 Stage 10 – Carbon Emission Evaluation

Upon completion of the training activity, the trial was performed and the environmental impacts measured. The results from the TPM activity in experiment 3 formed the new base to measure from for this experiment.

Table 32: Standardized work vs. anticipated result

Standardized work	Anticipated Result
1. Obsolete UPR x LWR Tack stage	- Reduced Air consumption - Reduced Gas consumption - Reduced Electrical consumption - Reduced Wire usage
2. UPR x LWR increased work content	- Increased Gas consumption - Increased Electrical consumption - Increased Wire usage
4. INSPECTION increase work content	- Increased Gas consumption - Increased Electrical consumption - Increased Wire usage

Utilizing the knowledge gained from experiments 1 and 3, Table 32 illustrates the anticipated benefits from the experiment.

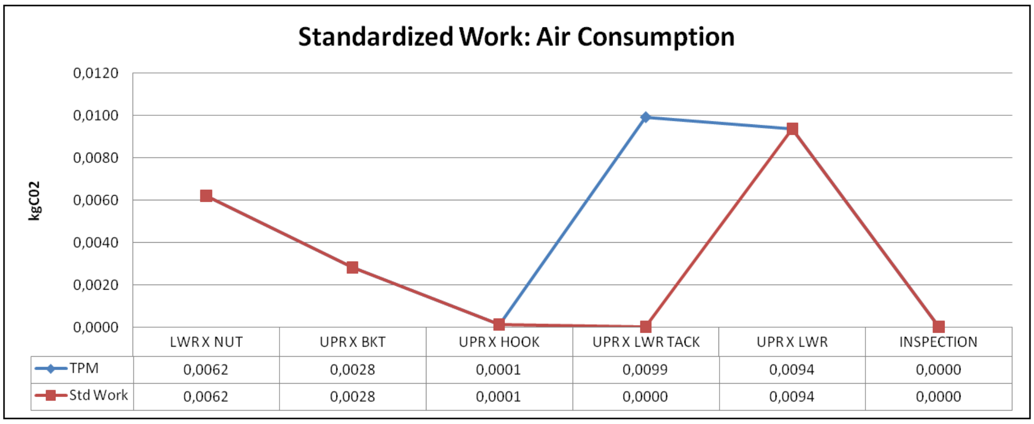
4.5.8 Air Measurement

The air measurement results from the TPM experiment were utilized, except for the UPR x LWR Tack.

Table 33: Compressed air emission conversion

Std Work Readings	Facility	$\overline{X}$	Compressor Power Consumption	Unit	Electricity Emission	Unit
	LWR X NUT	0,042	0,0065	kWh	0,0062	kgC02
	UPR X BKT	0,019	0,0029	kWh	0,0028	kgC02
	UPR X HOOK	0,001	0,0001	kWh	0,0001	kgC02
	UPR X LWR TACK	0,000	0,0000	kWh	0,0000	kgC02
	UPR X LWR	0,063	0,0098	kWh	0,0094	kgC02
	INSPECTION	0,000	0,0000	kWh	0,0000	kgC02
	Total	0,125	0,0193	kWh	0,0185	kgC02

The UPR x LWR Tack station consumption has become zero and the process is now redundant. Although the UPR x LWR stage took some of the work content, the air consumption remained the same as the weld fixture underwent the same production volume. Hence, taken as a whole, $0.0185\ kgC0_2$ will be emitted during the air consumption process for the manufacturing of one Auxiliary Cross Member.



Graph 13: TPM vs. Standardized Work - Air Consumption

Evaluating the total system, the TPM activity achieved a saving of $0.010\ kgC0_2$ of emissions per part which equated to a further 35% reduction in emissions.

4.5.9 Shielding Gas Consumption

The TPM results were once again utilized with the exception of the UPR x LWR Tack, UPR x LWR, and INSPECTION processes. The measured results yielded the following:

Table 34: Standardized Work Implementation - Gas Consumption

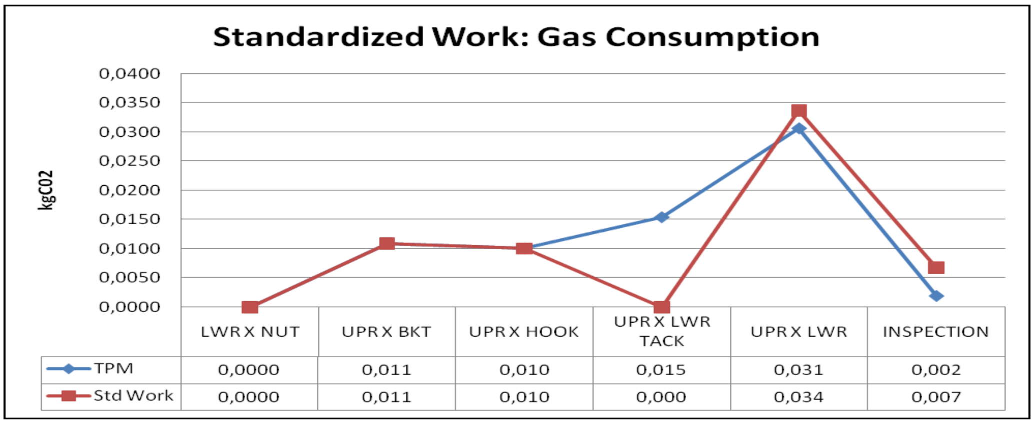
Lean Tool: Standardized Work																													
Std Work Readings	**Facility**	**Unit**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**	**S23**	**S24**	**S25**	**S26**	**$\bar{X}$**
	LWR X NUT	kg																											
	UPR X BKT		0,011	0,011	0,011	0,011	0,011	0,011	0,008	0,014	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011
	UPR X HOOK		0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,011	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010
	UPR X LWR TACK		0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	UPR X LWR		0,033	0,034	0,034	0,035	0,033	0,034	0,034	0,038	0,031	0,031	0,035	0,034	0,032	0,036	0,033	0,034	0,034	0,035	0,033	0,034	0,034	0,033	0,035	0,035	0,032	0,034	0,034
	INSPECTION		0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,006	0,007	0,006	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007
	TOTAL		0,061	0,062	0,062	0,063	0,060	0,062	0,059	0,069	0,059	0,060	0,063	0,062	0,059	0,064	0,061	0,062	0,061	0,062	0,060	0,061	0,062	0,061	0,062	0,063	0,060	0,062	0,062

The results reflected the UPR x LWR Tack process indicating zero as it was a redundant facility. However, both the UPR x LWR and INSPECTION processes had an increase in consumption due to additional weld content. The usage is described further in Table 35.

Table 35: Total Gas Consumption

	Facility	C02 Emmision	Unit
Std Work Readings	LWR X NUT	0,0000	kgC02
	UPR X BKT	0,011	kgC02
	UPR X HOOK	0,010	kgC02
	UPR X LWR TACK	0,000	kgC02
	UPR X LWR	0,034	kgC02
	INSPECTION	0,007	kgC02
	Total	0,062	kgC02

According to Table 35, $0.062\ kgC0_2$ was emitted on average due to shielding gas per Auxiliary Cross Member during production.



Graph 14: TPM vs. Standardized Work - Shielding Gas Consumption

The increase in the UPR x LWR and INSPECTION processes was offset by the redundancy of the UPR x LWR Tack station, resulting in a saving of 11%.

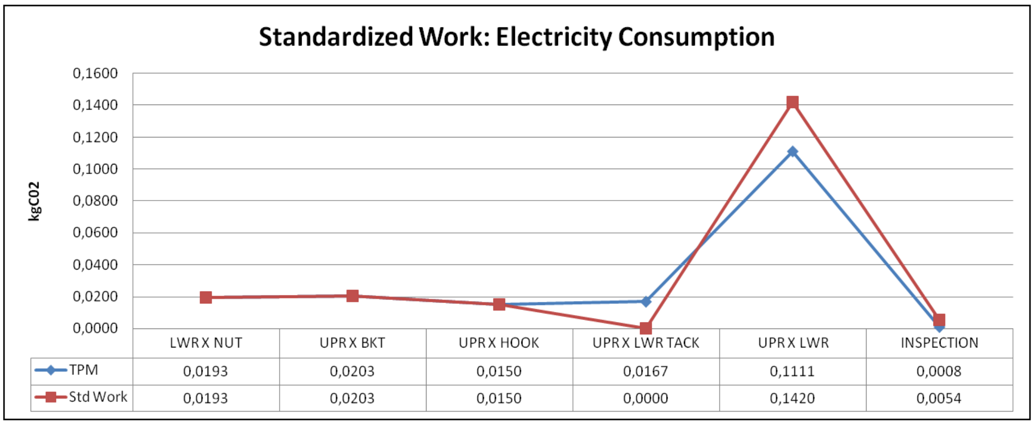
4.5.10 Electricity Consumption

The line balancing activity affected the welding contents in the INSPECTION and UPR x LWR processes. During the TPM condition, only the manual welding settings were changed and not the automation stage. The same was applied to this experiment. The UPR x LWR process was adjusted for more welding, while retaining the same voltage and current settings. Table 36 shows the results with the use of the power logger:

Table 36: Electricity emission conversion

	Facility	Weld machine Power Consuption	Unit	Electricity Emmision	Unit
Std Work Results	LWR X NUT	0,0202	kWh	0,0193	kgC02
	UPR X BKT	0,0212	kWh	0,0203	kgC02
	UPR X HOOK	0,0157	kWh	0,0150	kgC02
	UPR X LWR TACK	0,0000	kWh	0,0000	kgC02
	UPR X LWR	0,1482	kWh	0,1420	kgC02
	INSPECTION	0,0057	kWh	0,0054	kgC02
	Total	0,2109	kWh	0,2020	kgC02

The completion of the standardized work resulted in a usage of $0.2109\ kWh$ used for the welding operation in the manufacturing process of the Auxiliary Cross Member. This translated to $0.2020\ kgC0_2$ emissions emitted into the environment. Graph 15 illustrates the before and after saving in emissions due to Standardized Work:



Graph 15: TPM vs. Standardized Work - Electricity Consumption

The electricity consumption increased by 10% when compared to the results from the TPM experiment. The largest contributors, as anticipated, were the weld contents in the INSPECTION and UPR x LWR processes.

As seen in experiment 3, the weld content had a direct influence on the wire usage. The wire consumption was once again measured and the results tabulated:

Table 37: Standardized Work - Wire consumption

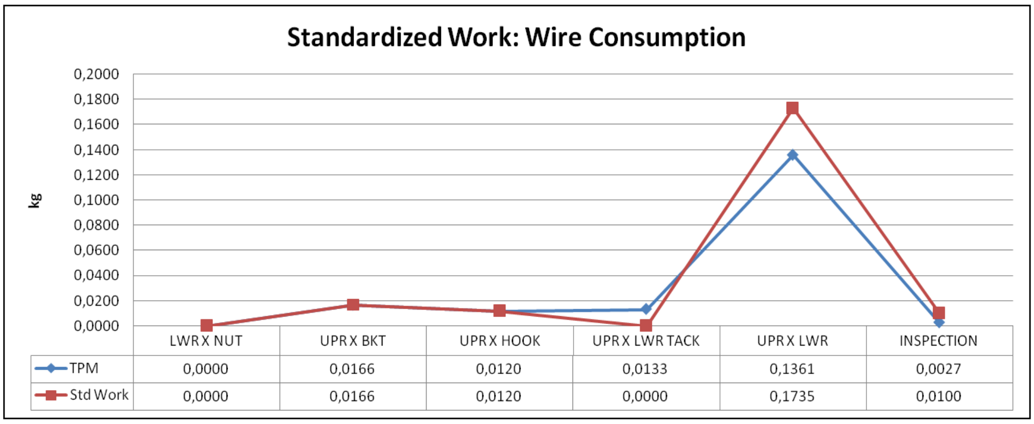
Lean Tool: Standardized Work																														
	Facility	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	$\overline{X}$
Std Work Readings	LWR X NUT	cm																											
	UPR X BKT		223,0	237,0	192,0	180,0	210,5	191,0	196,0	177,0	171,0	171,0	168,0	182,5	193,5	186,0	173,5	190,0	206,0	194,5	215,5	216,0	179,0	181,5	193,0	186,5	171,5	177,5	190,9
	UPR X HOOK		146,0	159,0	134,5	140,0	127,5	141,0	133,5	157,0	131,0	138,0	139,0	136,0	145,0	123,5	120,0	134,0	145,0	146,0	127,5	149,5	151,0	135,5	128,0	124,5	134,0	140,5	137,9
	UPR X LWR TACK		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	UPR X LWR		2051,3	1971,7	1991,6	2031,4	2051,3	1991,6	1991,6	1971,7	1991,6	2011,5	1991,6	1971,7	2031,4	1951,8	1931,9	1971,7	2031,4	1951,8	1931,9	2011,5	1991,6	1991,6	2011,5	1991,6	2051,3	1991,6	1994,7
	INSPECTION		108,0	101,0	118,0	84,0	115,5	101,5	112,0	106,5	125,5	110,0	109,5	123,0	116,0	121,0	118,5	113,5	128,0	120,0	123,5	111,5	109,0	144,0	109,5	120,0	111,0	123,0	114,7
	TOTAL		2528,3	2468,7	2436,1	2435,4	2504,8	2425,1	2433,1	2412,2	2419,1	2430,5	2408,1	2413,2	2485,9	2382,3	2343,9	2409,2	2510,4	2412,3	2398,4	2488,5	2430,6	2452,6	2442,0	2422,6	2467,8	2432,6	2438,2

The measurement resulted in the UPR x LWR and INSPECTION processes having an increased usage. The remaining stages have the same readings as those obtained in Experiment 3 except for UPR x LWR tack, which was zero. Thus, total wire usage per Auxiliary Cross was $2438.2\ cm$.

Table 38: Wire consumption conversion

	Facility	$\overline{X}$	Usage kg	Unit
Std Work Readings	LWR X NUT	0,000	0,0000	kg
	UPR X BKT	190,885	0,0166	kg
	UPR X HOOK	137,942	0,0120	kg
	UPR X LWR TACK	0,000	0,0000	kg
	UPR X LWR	1994,664	0,1735	kg
	INSPECTION	114,731	0,0100	kg
	Total	2438,222	0,2121	kg

To understand the consumption of wire in relation to the unit measured, the usage was converted to kg. The average usage per Auxiliary Cross Member was $0.2121\ kg$.



	LWR X NUT	UPR X BKT	UPR X HOOK	UPR X LWR TACK	UPR X LWR	INSPECTION
TPM	0,0000	0,0166	0,0120	0,0133	0,1361	0,0027
Std Work	0,0000	0,0166	0,0120	0,0000	0,1735	0,0100

Graph 16: TPM vs. Standardized Work - Wire consumption

The graph demonstrates the points of reducing and increasing wire usage. From the data, it can be gathered that there was an increase of 17% in wire usage. Wire usage translates to a landfill waste condition. The following table 39 depicts this:

Table 39: Wire usage drum conversion

Production Volume and wire usage - Standardized Work							
Montly Volume	JUN	JUL	AUG	SEPT	OCT	NOV	Total
	8093	8717	9280	9199	9792	8668	53749
Wire Usage	1717	1849	1968	1951	2077	1839	11402
Drum usage	6,867	7,396	7,874	7,806	8,309	7,355	46

Based on the 6-month production volume forecast, the 17% increase in wire usage per unit equated to a total wire usage of $11402\ kg$. This converted to a 46-drum usage over the production forecast, which was an increase of 6 drums over Experiment 3. The increase in solid waste that would be used for landfill was calculated to be $51.6\ kg$.

4.5.11 EVSM Evaluation: Standardized Work

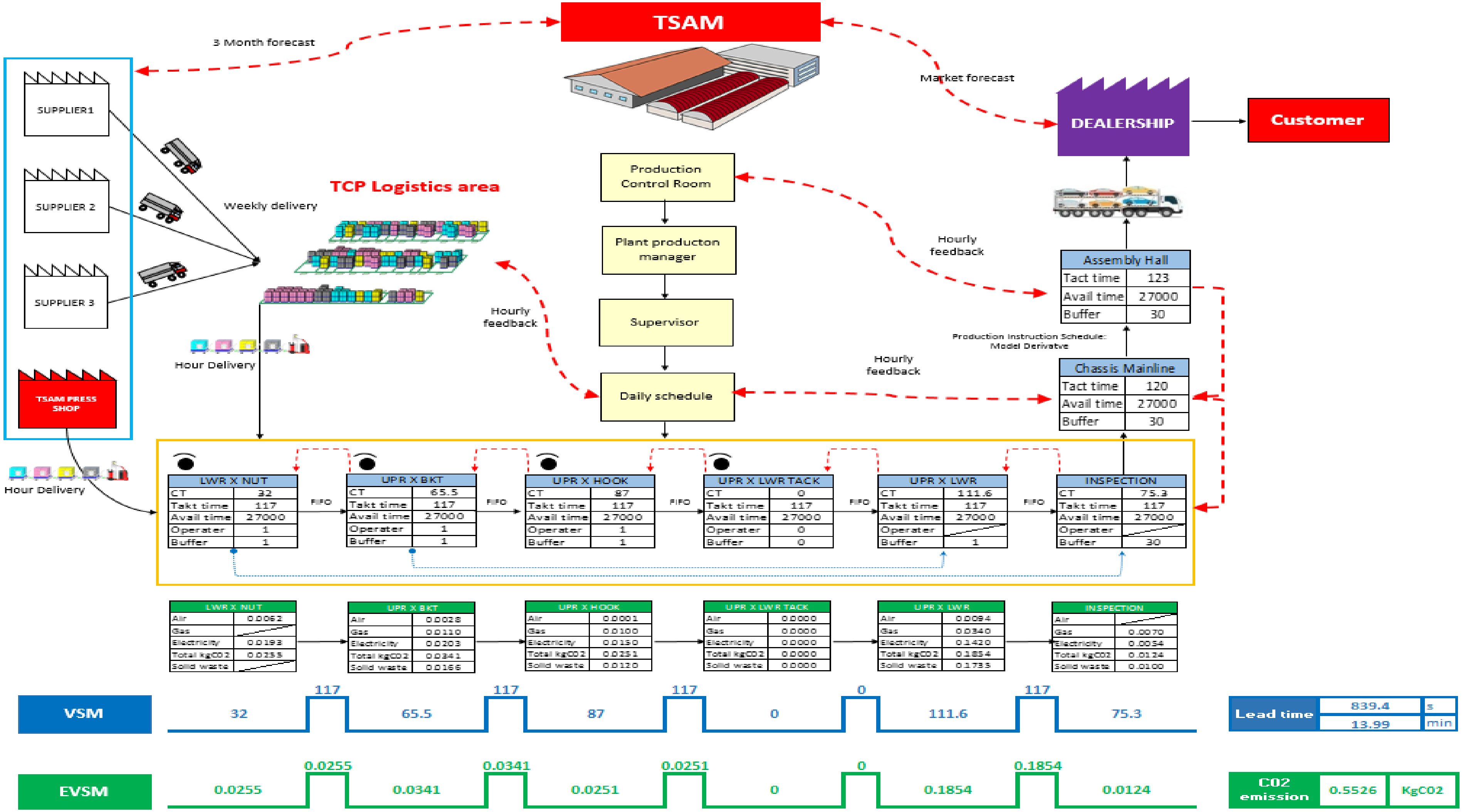


Figure 35: EVSM evaluation - Standardized Work. Adapted from Chiarini (2014)

The Standardized Work Experiment has reduced a process, a weld facility, an operator and in-process inventory. The lead-time has been decreased from 16.73 minutes to 13.99 minutes. This was largely due to the decrease in inventory at the UPR x LWR Tack process that was no longer required. Hence, the carbon emissions associated with that inventory have also become redundant. This again proves that E-VSM is a valuable tool in mapping environmental impacts as it has enabled the visualization of the full effect of the experiment. Secondly, it has illustrated that reducing inventory, one of the 7 lean wastes, leads to a positive effect on the environment.

The E-VSM illustrates a total of $0.5526\ kgC0_2$ emitted for each Auxiliary Cross member built. When compared to the TPM E-VSM of $0.5584\ kgC0_2$in Experiment 3, the Standardized work has demonstrated a 1% decrease in measured emissions emitted.

4.5.12 Experiment Summary

There is no doubt that the Standardized Work methods are powerful and effective tools in reducing wasteful activities and lead-time. However, the application of Standardized Work within this experiment seems to have had only a weak effect on reducing environmental impact.

In saying this, the Engineering and Maintenance team reviewed the results and stated that there would be a higher saving if the energy saving of the lights and ventilation were taken into account, along with the solid waste from spatter generation and disposable PPE. However, these benefits were not measured due to time and resource constraints. Hence, the theoretical finding F_3 that Standardized Work can affect environmental impacts in a positive way can neither be rejected nor accepted and requires further investigation.

4.6 Conclusion

The chapter presented the results of the experimental study. The specific lean tools were highlighted within each experiment. The results quantitatively revealed the following:

- VSM can be used as a tool for mapping and identifying the impacts on the processes of plant layouts.

- TPM, when fully implemented, can affect environmental impacts in a positive way.
- Standardized work, for the experiment within the specified context, has a minimal effect on environmental impacts.

Although Standardized Work had a minimal effect on environmental impacts, it has highlighted opportunities for improvement in future studies. Based on the analysis and presentation of results, the following chapter will present the conclusion and recommendations of the project.

Chapter 5

Conclusion and Recommendations

5.1 Introduction

This chapter presents an overview of the research accomplished through the theoretical and empirical studies. The findings and conclusions are based on the Lean initiatives and their respective contributions to enhance environmental performance. The first part of the chapter summarizes the theoretical and empirical findings of the work carried out in chapters 2, 3, and 4. Thereafter the limitations of the study are discussed, followed by the concluding remarks to validate the study. The final section of the chapter makes recommendations for the manufacturing industry, as well as for future studies.

5.1.1 Summary of Theoretical Study

Chapter 1 exemplified how Lean manufacturing has been at the forefront of the manufacturing sector as a strategic framework that has allowed for competitive advantage and operation expansion. Similarly, the literature review began by highlighting the array of tools Lean has to offer and their contribution to not only the automotive industry, but also to other comparable manufacturing operations. An analysis of the views of both academics and practitioners showed that the most popular tools utilized were VSM, TPM, Standardized Work and Continuous Improvement as they provided the most benefits.

New management systems, frameworks and strategies to increase environmental performance that included the ISO System, LCA and 3R were also reviewed. The key findings showed that although these frameworks provided a structured approach, many authors suggested that they should be integrated with existing manufacturing systems in order to gain maximum benefit. Further paradigms such as Green Manufacturing, Benchmarking and Eco-Innovation have additionally been reviewed. However, it was found that these environmental paradigms have not been clearly quantified.

Finally, the effect of Lean Manufacturing on the environment was analysed. The analysis reviewed conceptual studies and empirical work done by various authors and researchers.

The conceptual reviews considered whether Lean could improve environmental performance and provide a foundation for the paradigm. The empirical work complemented the conceptual work and justified that Lean had positive effects and synergies on the environmental aspects of manufacturing processes.

Based on the essential Lean tools and the work from previous practitioners, the research intended to add to the existing body of knowledge by implementing these tools and observing the positive effect on the environment within the South African Automotive Industry.

5.1.2 Summary of Empirical Findings

The empirical component of the research intended to test the theoretical findings from the literature review and evaluate the effects on environmental performance. The relationships between Lean tools, Lean wastes and Green wastes were conceptualised within the methodology section. Using these concepts, the respective experiments were designed to quantitatively test the relationships.

The preliminary work experiment was used to test the feasibility of the study and create a base line set of results. Thereafter, following the guidelines of the experiment design, each Lean tool was tested.

5.1.2.1 Value Stream Mapping

In the case of VSM, the following results were obtained:

Table 40: Effect of VSM on GHG emissions

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	VSM	0,9945	0,9945	0,0000	$kgCO_2$
Control Group		0,9945	0,9945		

Table 41: Effect of VSM on solid wastes

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	VSM	0,2018	0,2018	0,0000	kg
Control Group		0,2018	0,2018		

The findings from the literature review illustrated that VSM could be used as a tool to map and identify the environmental impact in the processes of a production plant.

The experimental design equation resulted in a zero, or net, effect for GHG emissions, or solid wastes. However, this did not demonstrate the true effect of the technique. Instead, VSM allows one to visualize and magnify the environmental performance of the process. This ensures simpler tracking and quantifying of environmental performance at various stages. It further allows for the prioritization of improvement activities that will deliver maximum benefit. Therefore, the traditional VSM was adapted to exhibit environmental impact and can be more readily accepted within the environmental community.

5.1.2.2 Total Productive Maintenance

The following results were captured during the TPM experiment:

Table 42: Effect of TPM on GHG emissions

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	TPM	0,9945	0,5584	-0,4361	$kgCO_2$
Control Group		0,9945	0,9945		

Table 43: Effect of TPM on solid wastes

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	TPM	0,2018	0,1807	-0,0211	kg
Control Group		0,2018	0,2018		

The intention was to test the positive effects of TPM on environmental performance gathered from the theoretical findings. Through the experiment, a reduction of 0.4361 $kgCO_2$ in GHG emissions and 0.0211 kg in solid wastes per part produced was achieved. TPM proved to have the most significant effect on environmental performance and highlighted that equipment that was regularly maintained to operate at optimum conditions reduced non-value adding energy usage.

5.1.2.3 Standardized Work

The Standardized Work experiment provided the following results:

Table 44: Effect of Standardized Work on GHG emissions

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	Standardized Work	0,5584	0,5526	-0,0058	$kgCO_2$
Control Group		0,5584	0,5584		

Table 45: Effect of Standardized Work on solid wastes

Group	Treatment	Pre - Test	Post Test	Result	Unit
Experimental Group	Standardized Work	0,1807	0,2121	0,0314	kg
Control Group		0,1807	0,1807		

Standardized Work has shown a saving of $0.0058\ kgC0_2$ in GHG emissions and an increase of $0.0314\ kg$ in solid waste usage per part produced. Though this tool has shown minimal benefits within the context of this study, further examination of the tool needs to take place to better understand its usefulness.

In comparing the outcomes, the study found significant differences in the pre-test and post-test results of each Lean technique applied. Taken together, a total of $0.4419\ kgC0_2$ in GHGs per part manufactured have been reduced. The solid wastes have increased by $0.0104\ kg$ per part, mainly due to standardized work.

Nevertheless, the results are consistent with the theoretical findings, except for standardized work. However, this identifies opportunities for further investigation and improvement of Lean and environmental performance.

5.1.3 Achievement of the Aim and Objectives

The primary objective of the study was based on the researcher's intention to create a framework that could improve current environmental performance through Lean Manufacturing. The Lean factors that contributed to waste reduction substantially were identified through an extensive review of literature, detailed through the methodology, and quantitatively tested through a series of experiments.

Chapters 2, 3 and 4 provided support for the objectives of the study and formed the backbone of the research. Firstly, the theoretical findings of chapter 2 led to the conceptual framework that Lean tools could positively affect environmental performance. Chapter 3 proceeded to detail how each Lean tool should be utilized to improve activities.

Secondly, the findings in chapter 4 have extensively demonstrated the measurement of GHG emissions within a production environment and illustrated how a specific Lean tool can reduce or mitigate GHG emissions.

5.1.4 Restrictions and Limitations

The limitations arising from this study could lead to opportunities for future research. The research was conducted within the automotive sector of the manufacturing community. The findings were valid for this sector; however, they could present an opportunity for improved environmental performance in other sectors. For instance, standardized work could provide greater returns in a different manufacturing scenario. Further quantitative research is required to understand whether these results would be similar if the research was conducted in different industries and to find out how to make them more mainstream and comprehensive.

Another key limitation was that tools that measure other GHG emissions, such as hazardous fumes and liquids, were not readily accessible. However, the most significant limitation was the restriction on obtaining a large enough sample size to avoid jeopardizing the production volumes.

5.1.5 Conclusion

The manufacturing industry is under extreme pressure to become more competitive while conducting operations that continuously meet the requirements of environment sustainability. This forces practitioners to become more dynamic and constantly innovate manufacturing processes.

The organization in which the research was conducted thrives on the principles of Lean Manufacturing. In conjunction with the production system, the ISO system has been implemented and is in common practice. Regardless of these attributes, further opportunities for improvement were presented using the selected Lean tools. Therefore, it could be deduced that even though companies do practise Lean manufacturing and operate in terms of the ISO certification, it is always possible to improve performance.

These findings agree with the findings of Zackrisson, Avellán and Orlenius (2010), Chiarini (2014) and Garza-Reyes *et al*. (2018) reviewed in chapter 2. Hence it can be summarized that Lean Manufacturing could be used as a method of reducing GHGs, with the stipulation that the entire organization should be committed to practising it. Furthermore, the ISO system should be seen as a guiding principle and needs to be integrated into an existing production system to function and gain sustainable benefits.

These findings are beneficial as they contribute to gaining a better understanding of the way lean tools and techniques affect environmental performance. The study provided a good perspective on these relationships, which has contributed to the current body of knowledge. Small to medium enterprises, practitioners and larger organizations could utilize this study for strategic development and simultaneous implementation of Lean Green operations.

5.2. Recommendations

5.2.1 Introduction

This section highlights the recommendations based on the findings of the research undertaken. Additionally, recommendations for the manufacturing industry and future studies have been included.

5.2.2 Recommendations based on findings

The research findings verified that the Lean and Green paradigm has the potential to change the manufacturing world while retaining sustainable operations. Although the empirical findings in Chapter 4 support this potential, they have also highlighted the following opportunities for improvement:

Table 46: Recommendations based on findings

Lean Principle	**Recommendation**	**Expected Outcomes**
VSM	The VSM evaluation is considered to be on a smaller scale, when compared to the entire plant.	Evaluation of the entire plant operation provides a more holistic view and creates greater opportunity for improvement.
	Further evaluations of additional GHG emissions such as lighting and transportation.	Understanding the effect of more GHG emissions within a supply chain context emphasises that the Lean Green paradigm can be used in both manufacturing and logistics operations.
	The analysis of the internal and external supply chain operation.	
TPM	Only the autonomous improvements were carried out. More improvements from an engineering level need to be understood.	Engineering improvements allow for additional GHG emission improvements as well as detailed studies of new standards/ benchmarks to be developed.
	The training of employees to understand the effects of using equipment that is not in optimum condition.	Training of employees enables awareness and stimulates pro-activeness to understand this and ensure optimal condition of equipment.
Standardized Work	A greater number of GHG emissions need to be measured to better understand the benefits of Standardized Work (e.g. Weld fumes, Reject parts, Daily PPE waste).	Evaluating more GHG emissions may allow for the consideration that Standardized Work has a beneficial effect on environmental performance.
	Further studies on robust optimization techniques need to be undertaken in an effort to streamline shielding gas usage and weld parameters.	Optimization techniques will allow for further reductions and help demonstrate the beneficial effects of Standardized Work.

It is recommended that a considerable amount of work should still be undertaken to further lean out the GHG emissions within the plant operations. This would involve a thorough understanding of the E-VSM in an effort to target an increased reduction of emissions. More preparation in respect of training would be required to allow operators and artisans to be more aware and proactive. Further support from the Engineering team would be required to share knowledge and improve current standards. Finally, with the combination of E-VSM and an understanding of additional GHG's, Standardized Work could achieve a greater emissions reduction.

The factors mentioned above show that there is the potential to gain further benefits from using the current lean techniques. The underlying principle of Lean Manufacturing is to standardize and continuously improve activities, thus the necessary techniques need to be mastered in order to fully achieve these benefits.

5.2.3 Recommendations based on study

The fundamental objective of the research was to develop a framework that would benefit environmental performance using current knowledge of manufacturing systems. Through the research findings, the positive effects of Lean Manufacturing on the environment have been substantiated. These findings have also strengthened the foundation of the Lean Green paradigm.

Following on from this, it can be deduced that for the framework to function appropriately, the principles of Lean Manufacturing need to be nurtured throughout the organization. The employees of an organization were critical to the success of Lean Manufacturing (Verrier, Rose and Caillaud 2016). Hence, training on Lean Manufacturing and the effect it has on the environment needs to be emphasised and presented on an ongoing basis.

A key principle of Lean is the ability to implement, standardize and improve continuously. Additional Lean tools should be introduced and the environmental benefits understood. Further theories could be developed to a point where the benefits are more generally accepted, allowing for easier implementation.

This would build on the current Lean philosophy and strengthen the Lean Green paradigm, which would eventually lead to an enhanced manufacturing system that could support a sustainable future.

5.2.4 Recommendations for the Manufacturing Industry

The framework and findings of this study should be applied to other critical areas within both the automotive sector and other manufacturing industries. South African SMEs would largely benefit from these research results for the following reasons:

- Lean Manufacturing would enhance productivity and allow for quality improvements while reducing the overall cost of products. Although this is already understood, it needs to be regularly emphasised to support the thinking behind continuous improvement.
- Additional benefits would be gained in the form of environmental performance, providing a platform for SMEs to become more robust and dynamic.

Additionally, knowledge about the Lean green paradigm should be continuously developed, practised and shared between larger organizations and SMEs. This knowledge sharing would allow for the extension of the paradigm and benefits across the manufacturing industry allowing for expansion into supply chain operations.

5.2.5 Recommendations for Future Research

This section presents recommendation for future research. These include:

- Further development of the framework, which would provide details on the implementation of additional Lean tools and proposed outcomes.
- Using a larger population and sample size to more fully understand the effects of the Lean tools applied.
- Undertaking empirical studies of a similar nature in other industries to further develop the paradigm and compare cases for easier implementation.

5.3 Concluding remarks

The future of the manufacturing industry depends on its capability and capacity to adapt to changes to create a sustainable future. The research has substantiated how a well-established manufacturing system could be utilized to achieve increased environmental performance. Additionally, it has emphasised the need for industry to adapt and innovate. Adaptation refers to working within the policies and procedures of Lean Manufacturing, while innovation requires an understanding of the environmental crisis and how to use Lean Manufacturing effectively to generate solutions which could lead to a more sustainable manufacturing industry in the future.

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List of Annexures

Annexure A: Letter of Permission

DUT DURBAN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF INDUSTRIAL ENGINEERING

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

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August 26, 2020

To whom it may concern,

Permissions to conduct research as part of the Masters (MEng) programme in Industrial Engineering

Name: Mr Keshav Ramsunder

Student No: 20702619

Title: The application of lean principles to mitigate greenhouse gas emissions in an automotive industry.

It is a requirement of the Masters (MEng) programme in Industrial Engineering that a student undertaking a full research degree should do field work at this level.

Typically, this research dissertation will be a "practical problem solving" exercise, and necessitates data gathering by experiments on the production lines of Toyota Chassis Plant.

Your assistance in permitting access to your organisation for the purposes of this research is most appreciated. Please be assured that all information gained from the research will be treated with utmost circumspection. Further, should you wish to view the result or outcome from the thesis, this can be arranged.

Confidentiality and anonymity will be strictly adhered to by the student. If permission is granted, then the Durban University of Technology requires this to be in writing on a letterhead and signed by the relevant authority.

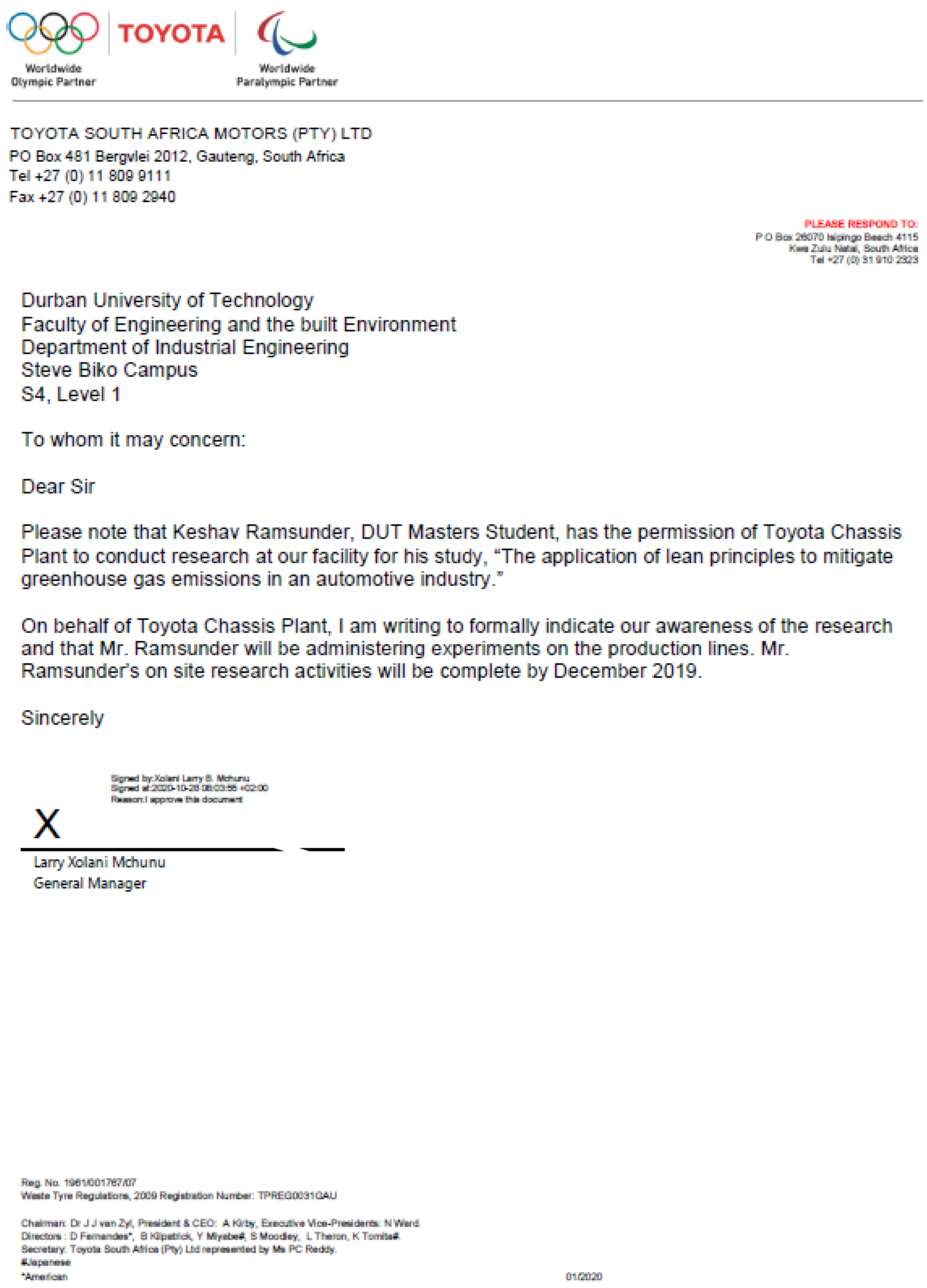
Many thanks for your assistance in this regard.

Yours sincerely

Keshav Ramsunder

Signed by:Keshav Ramsunder
Signed at:2020-10-23 10:14:25 +02:00
Reason:I approve this document

Annexure B: Letter of Consent



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Durban University of Technology
Faculty of Engineering and the built Environment
Department of Industrial Engineering
Steve Biko Campus
S4, Level 1

To whom it may concern:

Dear Sir

Please note that Keshav Ramsunder, DUT Masters Student, has the permission of Toyota Chassis Plant to conduct research at our facility for his study, "The application of lean principles to mitigate greenhouse gas emissions in an automotive industry."

On behalf of Toyota Chassis Plant, I am writing to formally indicate our awareness of the research and that Mr. Ramsunder will be administering experiments on the production lines. Mr. Ramsunder's on site research activities will be complete by December 2019.

Sincerely

Signed by:Xolani Larry B. Mchunu
Signed at:2020-10-28 08:03:56 +02:00
Reason:I approve this document

X

Larry Xolani Mchunu
General Manager

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Directors : D Fernandes*, B Kilpatrick, Y Miyabe#, S Moodley, L Theron, K Tomita#.
Secretary: Toyota South Africa (Pty) Ltd represented by Ms PC Reddy.
#Japanese
*American

01/2020