Addis Ababa University

College of Technology and Built Environment

School of Mechanical and Industrial Engineering

Application of Green Lean Six Sigma (GLSS) through DMAIC Approach: A Case of Walia Steel Industry (WSI)

A Master's Thesis Submitted to School of Graduate Studies of Addis Ababa College of Technology and Built Environment, Addis Ababa University in Partial Fulfillment for Degree of Masters of Science in Industrial Engineering

By: Seble Negash

Advisor: Dr. Yitagesu Yilma

Co-Advisor: Birhanu Tolosa

Addis Ababa, Ethiopia

June, 2025

Addis Ababa University

College of Technology and Built Environment

School of Mechanical and Industrial Engineering

Industrial Engineering Chair

Title: Application of Green Lean Six Sigma (GLSS) through DMAIC Approach: A Case of Walia Steel Industry (WSI)

Submitted By Seble Negash (ID No. GSE/8200/12)

Approved by Board of Examiners

Dr Yitagesu Yilma Advisor	-------------------- Signature	04/08/2025 Date
Birhanu Tolosa Co – advisor	for -------------------- Signature	04/08/2025 Date
Dr Ermias Tesfaye Internal Examiner	for -------------------- Signature	04/08/2025 Date
Dr Amha Mulgeta External Examiner	-------------------- Signature	04/08/2025 Date
Dr Abdulkadir Aman Interim Head, SMIE	-------------------- Signature	04/08/2025 Date
Dr Shegaw Ahmed Interim vice Executive Dean for Academic Affairs, (CoTBE)	-------------------- Signature	-------------------- Date

Vice Executive Dean Office for Academic Affairs

College of Technology and Built Environment Addis Ababa University

Authors' Declaration

I, Seble Negash, declare that this thesis entitled "Application of Green Lean Six Sigma (GLSS) through DMAIC Approach: A Case of Walia Steel Industry (WSI)" is my original research work and no material has been submitted previously for the award of any other academic degree.

The research work was done under the guidance of Dr. Yitagesu Yilma at Addis Ababa University, College of Technology and Built Environment, School of Mechanical and Industrial Engineering.

Seble Negash	04/08/2025 Date

This is to certify that the above declaration made by the author is correct to the best of my knowledge.

Dr. Yitagesu Yilma	04/08/2025 Date
Birhanu Tolosa	04/08/2025 Date

Acknowledgments

First and foremost, I sincerely thank God for giving me the strength, patience, and guidance to complete this thesis.

I would like to express my deepest gratitude to my advisor, Dr. Yitagesu Yilma, and my co-advisor, Mr. Birhanu Tolosa, for their consistent support and encouragement throughout this research. Their valuable advice, thoughtful feedback, and willingness to share their knowledge have been truly instrumental in shaping this work.

I am also very grateful to all the staff members at Walia Steel Industry. Thank you for your cooperation, for openly sharing your insights and experiences, and for providing the necessary support to carry out this study effectively.

Last but not least, my heartfelt thanks go to my dear family and friends for always being there for me with love, encouragement, and understanding through every step of this journey.

Abstract

In today's manufacturing world, producing high-quality products while reducing waste and environmental harm is increasingly critical. This study explores the application of Green Lean Six Sigma (GLSS) an integrated framework combining Lean principles, Six Sigma methodologies, and sustainability practices within the Walia Steel Industry (WSI), a major steel profile manufacturer in Ethiopia. The research applies the DMAIC (Define, Measure, Analyze, Improve, Control) approach to assess and address rising product defects, which increased from 2.34% in 2022/23 to 3.06% in 2023/24, alongside growing material waste and emissions.

A mixed-method case study was employed, drawing on production records, interviews, and observational data. Analytical tools such as Pareto charts, Material Flow Analysis (MFA), simplified Life Cycle Assessment (LCA), fishbone diagrams, and the 5 Whys method were used to identify and analyze key defects in CHS, RHS, SHS, and LTZ products. Root causes were traced to poor machine calibration, substandard raw materials, and inadequate storage conditions. The process capability assessment revealed a DPMO of approximately 10,213, corresponding to a Sigma level of 2.6 for without 1.5σ shift and 3.8 for with 1.5σ shift. MFA projected 149.83 tons/year of material waste, while LCA estimated this waste contributes approximately 45 tons of CO_2 e emissions annually. Additionally, Lean wastes particularly Defects, Waiting, Motion, and Overprocessing were conceptually mapped using the TIMWOOD framework, based on qualitative observations.

As a result, the study proposes a tailored GLSS-based conceptual framework designed to reduce defects by an estimated 46.7%, potentially lowering CO_2 e emissions by 21 tons/year. The framework integrates Lean waste reduction, Six Sigma quality control, and Green sustainability tools across all DMAIC phases. This research fills a critical gap in the literature by demonstrating how GLSS can be applied in developing country contexts like Ethiopia to drive operational efficiency and environmental performance. The findings offer a scalable model for sustainable manufacturing applicable to similar industrial settings.ment.

Keywords: Green Lean Six Sigma (GLSS), DMAIC, Defect Reduction, Sigma Level, Sustainable Manufacturing, Material Flow Analysis (MFA), Life Cycle Assessment (LCA)

Table of Contents

List of Table:

List of Figure

List of Abbreviations

GLSS Green Lean Six Sigma

LSS Lean Six Sigma

MFA Material Flow Analysis

LCA Life Cycle Assessment

TIMWOOD Transportation, Inventory, Motion, Waiting, Overproduction, Overprocessing, Defects

DMAIC Define, Measure, Analyze, Improve, Control

WSI Walia Steel Industry

CHS Circular Hollow Section

RHS Rectangular Hollow Section

SHS Square Hollow Section

LTZ Lipped Channel Section (L-, T-, Z-shaped)

DPMO Defects per Million Opportunities

DQA Data Quality Assessment

EHS Environmental Health and Safety

HRM Human Resource Management

ISO International Organization for Standardization

MIS Management Information System

NDT Non-Destructive Testing

QA/QC Quality Assurance / Quality Control

SOP Standard Operating Procedure

TQM Total Quality Management

CHAPTER ONE

1. INTRODUCTION

1.1. Background and Justification of the Study

Quality management plays a critical role in both manufacturing and service sectors by improving efficiency, reducing variability, and enhancing customer satisfaction. Total Quality Management (TQM) laid the foundation for systematic quality improvement through continuous improvement, customer orientation, and standardized processes (Oakland, 2014). Over time, Lean Thinking focused on eliminating non-value-adding activities, while Six Sigma introduced a data-driven approach to minimize defects and reduce process variability (Antony, 2021). Integrating Lean and Six Sigma (LSS) offers a holistic improvement strategy that enhances speed, efficiency, and quality simultaneously. However, conventional LSS initiatives tend to emphasize economic outcomes, often neglecting environmental sustainability.

To address this gap, Green Lean Six Sigma (GLSS) was developed, integrating sustainability principles into LSS by systematically reducing waste, emissions, and resource consumption (Kaswan et al., 2023). This methodology ensures that manufacturing processes are not only cost-effective but also environmentally responsible, aligning with global sustainability standards.

Integrating Lean Six Sigma (LSS) with Green technology forms Green Lean Six Sigma (GLSS), a robust methodology aimed at improving organizational performance by systematically reducing waste, emissions, and non-value-adding activities. LSS is more likely to affect the economic dimension of the sustainability than the environmental due to wide variety of environmental metrics. GLS incorporates dimensions of the sustainability (Environmental and economic) and makes an organization more competitive at global platform. Sustainable Green Lean Sigma incorporates all dimensions of the sustainability (social, economic and environmental) and leads towards a resilient industry and health society. (Kaswan et al., 2023)

Nowadays Six Sigma and Lean become more powerful for solving many practical problems. The combination of these two improvement approaches plays big role in the current or 4th industrial revolution world. LSS is achieving 'high value and quality, minimum waste and variation' to be a world-class company for stakeholder satisfaction. In order to achieve this goal, two big pillars are needed. The first is the Lean approach by speed acceleration and waste reduction for process innovation. The second is the Six Sigma approach by reducing variation, defects reduction and efficient process flow using continuous improvements and innovation. LSS is that LSS allows not only process innovation with speed and waste reduction (by Lean), but also process efficiency with variation & defects reduction and efficient process flow (by Six Sigma)(Park et al., 2020). In other conference paper, it is stated that, Six Sigma is a method that eliminates defects in products. Different processes can be compared with defects per million opportunities (DPMO) value. As in every step of production, there is a chance of occurrence of defects. Six Sigma eliminates defects completely in a manufacturing process that can be only up to 3.4 defects per million opportunities, which means there can only up to 1 defect for every 294,000 units. It is achievable by improving the engineering practices used by the enterprises for its manufacturing operations. The paper describe DMAIC approach as a basics of LSS implementation (Jayaram, 2016).

The steel manufacturing industry, particularly at Walia Steel Industry, faces increasing defect rates, high material waste, and inefficient resource utilization. These challenges necessitate an advanced quality improvement approach that aligns with sustainability goals. This study explores the application of GLSS in steel manufacturing, aiming to improve product quality, production efficiency, and environmental impact reduction.

1.2. Problem Statement

Walia Steel Industry (WSI), a major Ethiopian manufacturer of steel hollow sections, is currently experiencing a rising trend in product defect rates. Internal production records show an increase from 2.34% in the 2022/23 fiscal year to 3.06% in 2023/24. These

rejection rates exceed both national and international benchmarks, which typically recommend maintaining defect levels below 2% to ensure structural reliability, minimize operational costs, and maintain customer satisfaction (Ma, Chan, & Young, 2017; Ministry of Industry, 2021)**.** The defects are not confined to a single product line but are widespread across Circular Hollow Sections (CHS), Rectangular Hollow Sections (RHS), Square Hollow Sections (SHS), and Lipped Channel Sections (LTZ).

In addition to quality concerns, these rising defect rates are contributing to significant environmental impacts, primarily through increased material waste and energy consumption. Rejected products often require reprocessing or are discarded, leading to inefficient resource utilization. This inefficiency contributes to elevated carbon emissions and environmental degradation.

Beyond the statistical increase, the significance of these defects lies in their direct impact on WSI's operational and competitive performance. Defective products require rework or replacement, leading to increased downtime, material waste, and production costs. Additionally, recurring defects signal underlying process inefficiencies and highlight gaps in the company's quality control systems. These inefficiencies are especially concerning in a manufacturing environment where rising production volumes are not supported by proportionate improvements in process stability or quality assurance.

The environmental implications of these quality problems are also critical. Each instance of rework consumes additional energy, materials, and resources, contributing to higher electricity and gas usage, greater carbon emissions, and increased solid waste. These sustainability concerns, coupled with escalating defect rates, indicate a need for a more holistic and integrated improvement strategy.

The challenges faced by WSI reflect a broader trend across Ethiopian manufacturing industries, where outdated machinery, limited process control, and inadequate quality management frameworks contribute to defect rates exceeding 2% (Tekle et al., 2020; Kebede & Worku, 2019). Despite national guidelines that promote sustainable and quality-focused manufacturing, capacity constraints remain a barrier to achieving such standards.

In manufacturing, increasing production volumes often lead to higher defect rates if quality control systems are not well structured. Defects are more likely to occur when production volumes rise, which results in more rework, waste, and worse customer satisfaction. (Colias, 2024). Organizations that prioritize quality management can lower failure rates, according to research, but many still find it difficult to keep this balance as production scales. This is evident in various sectors where efficiency efforts, without adequate quality monitoring, have led to a decline in product standards (Sadikin, 2023).

Therefore, it is crucial to establish quality control systems effectively in order to reduce the rise in defect rates that is frequently linked to increasing production quantities. However, real-world challenges in estimating error frequencies and overseeing quality control procedures often result in high defect rates, which negatively impact operational effectiveness and undermine customer confidence (Ali & Adhikari, 2024).

Table 1.1: Rejection rate

Product type	Production TON	2022/23 rejection rate %	Production TON	2023/24rejection rate %
CHS	729.72	2.0	596.76	2.7
RHS	931.91	2.3	749.86	2.8
SHS	1869.1	2.5	2260.92	3.1
LTZ	0	0	1288.98	3.27
Total	3530.73	2.34	4896.52	3.06

Source: company recorded data.

In the Ethiopian manufacturing context, similar challenges are prevalent. Studies by Tekle et al.., (2020) reveal that many Ethiopian steel producers experience defect rates at or above 2%, largely due to limited adoption of quality management systems, outdated machinery, and skill deficiencies. Kebede and Worku (2019) also found that small and medium manufacturing enterprises in Ethiopia typically report defect rates exceeding 2%, driven by insufficient quality assurance practices and limited lean manufacturing implementation. The Ethiopian Ministry of Industry (2021) recommends industrial quality standards targeting defect rates below 2% to enhance competitiveness and sustainability; however, resource and capacity constraints frequently hinder local manufacturers from achieving these goals.

Given this background, WSI’s rising defect rates along with increasing waste underscore the need for a structured improvement strategy that integrates both quality and environmental sustainability. This investigation is vital to develop effective, context-appropriate quality improvement strategies that will enable WSI to optimize production output, minimize defects, improve operational performance, improve environmental waste or impact and sustain competitiveness in both domestic and international markets. Given these challenges, there is an urgent need for a holistic approach that not only reduces defects but also minimizes environmental waste.

1.3. Research Questions

1) What are the major product defects and quality issues , along with their associated environmental impacts, in Walia Steel Industry’s hollow section production process, and how can these be identified and analyzed?
2) How can the GLSS framework through DMAIC be applied to identify root causes, reduce defects, and improve environmental performance in Walia Steel Indudustry?
3) What sustainable strategies can be applied to reduce waste and enhance operational performance in steel profile manufacturing sector?

1.4. Objectives

1.4.1. General objective

The General objective of this thesis is to apply Green Lean Six Sigma framework trough DMAIC approach for reducing defect and associated environmental impacts in case of Walia Steel Industry.

1.4.2. Specific Objective

- To identify and analyze the major product defects and quality problems , along with their associated environmental impacts, in Walia Steel Industry’s hollow section production.
- To evaluate the application of GLSS through DMAIC to analyze key product defects and assess their environmental implications.
- Propose a conceptual sustainable quality improvement framework for defect reduction and process optimization.

1.5. Scope

This study is limited to the analysis of product defects within Walia Steel Industry's hollow section manufacturing operations, specifically focusing on Circular Hollow Sections (CHS), Rectangular Hollow Sections (RHS), Square Hollow Sections (SHS), and Lipped Channel Sections (LTZ). The scope includes identifying major defect types, analyzing their root causes using selected Six Sigma tools (Pareto chart, Fishbone diagram, and 5 Whys), and assessing associated environmental and operational impacts.

The study applies the Green Lean Six Sigma (GLSS) framework through the DMAIC approach at a conceptual level. It does not involve actual implementation of process changes but instead develops a proposed improvement framework based on existing company data, observations, and literature. Environmental sustainability aspects such as emissions are considered qualitatively and with estimation from secondary data sources due to the absence of direct measurement data. Other Lean tools such as TIMWOOD are conceptually referenced but not empirically applied.

The study excludes other departments such as procurement, human resources, or maintenance, and does not address all possible forms of manufacturing waste beyond those directly linked to product defects. Financial cost analysis are outside the scope of this research.

1.6. Significance of the Study

This study is important as it addresses persistent issues of product defects and waste in Walia Steel Industry. The Green Lean Six Sigma (GLSS) DMAIC technique offers the company an organized way to cut waste, improves production processes, and decrease defects. It also contributes to the limited literature on GLSS implementation in developing countries, offering useful insights into combining sustainability with quality improvement. The results are in line with national objectives for environmental stewardship and industrial competitiveness, and they encourage industry efforts toward operational excellence.

1.7. Limitations of the study

This study focuses on a single case company Walia Steel Industry which allows for detailed analysis but may limit the generalizability of the findings to other manufacturing firms. One of the main challenges encountered was the lack of existing research on the application of Green Lean Six Sigma (GLSS) within the Ethiopian context. Most available literature is based on studies conducted in industrialized countries, where the manufacturing environment, infrastructure, level of automation, and management culture differ greatly from those in Ethiopia. As a result, it was difficult to find research that fully aligned with the realities faced by local manufacturers. This gap made it challenging to benchmark findings or draw direct comparisons, highlighting the need for more locally grounded research on sustainable quality improvement practices in Ethiopia's manufacturing sector. Another significant limitation is lack of measured environmental impact data from the case industry, which restricts the ability to quantify sustainability outcomes. Due to data constraints, environmental impacts emissions are estimated through secondary data rather than directly measured

1.8. Organization of the thesis

This thesis is structured into five chapters. Chapter one introduces the study by presenting the background and justification, followed by the problem statement, research questions, objectives, scope, significance, and limitations. Chapter Two provides a comprehensive literature review on quality improvement methodologies, including Lean, Six Sigma, and their integration into Green Lean Six Sigma (GLSS). It explores both global and local perspectives on sustainable manufacturing, identifies the relevance of GLSS to the Ethiopian context, and highlights existing research gaps. Chapter Three outlines the research methodology, detailing the research design, data collection methods, sampling techniques, and the analytical tools used particularly the DMAIC approach and Material Flow Analysis (MFA). Chapter Four presents the data analysis using the GLSS-DMAIC framework, identifying key defects, their root causes, and proposing a conceptual solution framework aimed at improving quality and sustainability. Finally, Chapter Five summarizes the main findings, answers the research questions, and offers recommendations for practical implementation and future research.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

This chapter provides an in-depth look at the existing literature related to defect reduction in manufacturing, with a special focus on how Green Lean Six Sigma (GLSS) and the DMAIC (Define, Measure, Analyze, Improve, Control) methodology are applied in practice. It integrates theoretical insights, conceptual models, and real-world studies to understand how GLSS supports process improvement, enhances quality management, and promotes more sustainable manufacturing operations.

The continuous enhancement of quality has become crucial due to growing competition in manufacturing industries. Effective quality improvement initiatives contribute to reducing defects, cutting expenses, and increasing profitability and competitiveness. To address these challenges, several methodologies have been developed, including Lean Manufacturing, Six Sigma, Lean Six Sigma, and Green Lean Six Sigma (GLSS) (Kaswan et al., 2023).

With an emphasis on DMAIC and Green Lean Six Sigma (GLSS) approaches, this literature review examines a variety of quality improvement tools. It explores key concepts, practical application, and current research gaps particularly in the production of steel profile in Ethiopia.

2.1.1 Quality Improvement in Manufacturing

Enhancing quality must be combined with a performance perspective. This objective is the focus of several quality philosophies, including the Theory of Constraints, Total Quality Management (TQM), Lean Manufacturing (LM), Six Sigma (SS), and Lean Six Sigma (LSS). A review of quality improvement tools identifies several key methods, such as DMAIC (Define Measure, Analyze, Control) , VSM (Value Stream Mapping), 5S (Sort, Set in Order, Shine, Standardize, and Sustain), JIT (Just in Time), Kaizen, Standardization, TPM (Total Productive Maintenance), Kanban (a lean tool to reach a pull system of quality), SPC (Statistical Process Control), FMEA (Failure Mode and Effects Analysis). These tools often categorized based on their approach and targeted objectives. Research results highlight the fact that, in competitive market environment a strong Quality Management System (QMS) is for meeting customer needs from a sustainable perspective. When properly implemented, methodologies such as Lean manufacturing (LM), Six Sigma (SS), and Lean Six Sigma (LSS) provide significant benefits, including cost reduction, lead-time minimization, and improved quality performance (Psarommatis et al., 2020)

The evolution of quality management has led to methodologies that emphasize continuous improvement, waste reduction, and defect minimization. Approaches such as Total Quality Management (TQM), Lean Manufacturing (LM), Six Sigma (SS), and Lean Six Sigma (LSS) have played a significant role in improving manufacturing performance (Laureani & Antony, 2012).

To enhance production quality, applying the tools of Quality Management tools and Human Resource Management in all the production departments of the company has role to the identification of the causes that affect employees involvement in the process of continuous improvement initiatives. Addressing these causes and actively involving employees in the process of continuous improvement has shown boost production efficiency, and reduce operational, thereby yielding measurable gains for the company (Blaga, 2020).

2.2. Lean Thinking

Lean manufacturing, originally developed within the Toyota Production System, is a philosophy centered on eliminating waste (muda), optimizing workflow, and delivering value to the customer (Womack & Jones, 1996). Its five core principles value identification, value stream mapping, flow, pull, and perfection guide organizations in streamlining operations to achieve process excellence.

Recent research reaffirms the utility of Lean practices in improving flexibility, cost-efficiency, and responsiveness, particularly in manufacturing environments that face high competition and fluctuating demands (Antony et al., 2022). Lean tools such as 5S, Kaizen, visual controls, and Value Stream Mapping (VSM) are systematically employed to identify and reduce non-value-adding activities, including unnecessary transportation, overproduction, motion, waiting, inventory, defects, and underutilized talent (Salah et al., 2022).

The Lean philosophy centers on the systematic elimination of seven categories of waste, commonly abbreviated as TIMWOOD: Transportation, Inventory, Motion, Waiting, Overproduction, Overprocessing, and Defects. These wastes do not add value from the customer's perspective and contribute to inefficiency, cost increase, and quality problems. Identifying and minimizing these wastes is essential for improving process flow, reducing cycle time, and supporting sustainable manufacturing objectives. In the context of Green Lean Six Sigma (GLSS), eliminating Lean wastes also contributes to reduced energy use, emissions, and resource loss, thereby aligning operational efficiency with environmental sustainability (Kaswan et al., 2023; Psarommatis et al., 2020).

In resource-constrained economies, Lean is especially applicable due to its focus on low-cost and high-impact process improvements. It allows companies to enhance efficiency without substantial investment in new technology. However, Lean's strong orientation toward speed and flow can, at times, neglect detailed statistical process control or deeper systemic analysis. Without complementary methods, Lean may overlook root causes of variation that compromise long-term quality.

Therefore, while Lean enhances throughput and eliminates operational inefficiencies, its limitations in handling variation and statistical rigor highlight the need for integration with Six Sigma and environmental strategies in broader improvement initiatives like Green Lean Six Sigma (GLSS).

2.3. Six Sigma principles

Six Sigma is a data-driven and statistically rigorous methodology focused on reducing process variation, improving quality, and enhancing customer satisfaction (Pyzdek & Keller, 2014). It aims to achieve near-perfection in product or process performance, targeting a defect rate of 3.4 defects per million opportunities (DPMO). At its core lies the structured DMAIC (Define, Measure, Analyze, Improve, Control) approach, which facilitates systematic problem-solving and continuous improvement.

The methodology leverages a suite of quantitative tools such as control charts, cause-and-effect (Fishbone) diagrams, process capability analysis, and hypothesis testing to identify root causes of defects, quantify process capabilities, and evaluate improvements (Antony & Snee, 2020). Six Sigma emphasizes data accuracy, measurement discipline, and statistical validation, making it highly effective for identifying chronic quality issues and optimizing process performance.

In manufacturing contexts, Six Sigma provides strong discipline for reducing waste through better control of process variability. For instance, sigma level calculations help quantify the performance of defect-prone stages, while Pareto analysis prioritizes the most impactful defect types. This makes Six Sigma particularly valuable in steel manufacturing, where precision, consistency, and defect control are critical to competitiveness.

However, Six Sigma implementation poses challenges in low-resource environments. It often requires trained personnel (e.g., Green Belts, Black Belts), reliable historical data, and organizational commitment to data collection and continuous measurement (Setijono & Dahlgaard, 2021). In Ethiopia and similar settings, these prerequisites can limit full-scale adoption, leading to partial or tool-based implementations without the depth of DMAIC.

Despite these barriers, studies show that adapted or hybrid Six Sigma approaches can still yield significant quality gains when tailored to local capabilities. This supports the relevance of integrating Six Sigma within a broader, sustainability-oriented framework like Green Lean Six Sigma (GLSS), particularly when paired with lean and green tools that compensate for data and resource limitations.

2.4. Concept of Lean Six Sigma

Lean Six Sigma (LSS) is the combination of Lean Manufacturing and Six Sigma methodologies. The combination of these two approaches creates a synergistic effect by enhancing continuous improvement efforts, reducing both defects and waste simultaneously (Mendonça Júnior, Farid, Montenegro, Thadani, Pedroso, & Oliveira, 2018).

Lean Six Sigma to maximize value for stakeholders by improving quality, reducing waste and variability, and enhancing customer satisfaction. It achieves this by combining the tools and principles from both Lean and Six Sigma. LSS has been widely adopted both in manufacturing and service industries, and its successful implementation in leading companies such as General Electric and Motorola has encouraged many organizations globally to replicate its results(Laureani & Antony, 2012).

One example in implementation of Six Sigma in an automotive parts producing industry, where the DMAIC (Define Measure Analyze Improve Control)was used to reduce rejection rate and increase the sigma level. Various statistical techniques were applied to analyze the data and to identify solutions. The study reviewed multiple related works demonstrating how Six Sigma significantly reduces rework, defect and production cost. Tools such as Pareto chart, cause and effect diagram and other SQC tools (Yadav & Sukhwani, 2016).

DMAIC remains one of the most widely used quality improvement methodologies. Initially developed by Motorola in the 1980s in US, DMAIC was later combined with Lean manufacturing principles to form Lean Six Sigma. This integrated approach is used extensively by leading companies to achieve breakthrough improvements. According to Aichouni et al. (2021), the LSS-DMAIC approach is highly effective in reducing waste, cycle time, and process variability, while also enhancing product and service quality. When properly implemented, it reduces operational costs, improves efficiency, and gives organizations a competitive edge.

Due to its proven ability to deliver high-quality outcomes, LSS has gained global popularity, offering both output and quality-based improvements. This methodology, which aims to achieve fewer than 3.4 defects per million opportunities (DPMO), has resulted in substantial cost savings and quality gains in well-known organizations such as General Electric, Dell Inc., and Xerox Corporation (Dogan & Gurcan, 2018).

2.5. Green manufacturing

Green manufacturing refers to the development and application of processes that reduce negative environmental impacts while maintaining economic viability and product performance. It aims to minimize the consumption of natural resources, reduce greenhouse gas emissions, and eliminate waste across the production life cycle (Jovane et al., 2008; Yang et al., 2021).

Key tools include Material Flow Analysis (MFA), which is used to quantify input-output relationships and identify waste hotspots in production systems, and Life Cycle Assessment (LCA), which evaluates environmental impacts from raw material extraction to finished product delivery. These tools support decision-making for eco-efficiency, product redesign, and sustainable resource use.

In both developed and developing countries, green manufacturing is gaining momentum as governments and industries align with the United Nations Sustainable Development Goals (SDGs). However, while developed nations often integrate advanced monitoring technologies and stringent regulatory compliance, industries in developing economies face challenges such as limited technical infrastructure, weak policy enforcement, and insufficient environmental awareness (Fatimah et al., 2023).

In the Ethiopian context, the transition toward green manufacturing is emerging in response to environmental degradation, energy inefficiencies, and material scarcity. Studies suggest that while awareness is growing, the practical application of green practices remains fragmented due to lack of training, data systems, and investment in cleaner technologies (Gebremedhin & Bekele, 2022). Basic but impactful initiatives such as improving storage to reduce corrosion, preventing material waste through better inspection, and applying low-cost recycling can generate substantial improvements.

Green manufacturing is increasingly relevant in both developed and developing countries as industries face pressure to decarbonize and align with sustainable development goals. In the Ethiopian context, Green manufacturing is gaining attention due to rising awareness of climate change, pollution, and resource scarcity (Gebremedhin & Bekele, 2022). Despite its promise, the practical application of green tools often lacks systemization and real-time performance tracking in low-technology settings.

2.6. Green lean

Green Lean is an approach that integrates Lean Manufacturing principles with sustainability goals to improve environmental performance. Dues, Tan, and Lim (2013) explored the concept and found that Green Lean positively impacts on green initiatives while complementing existing Lean practices. By incorporating environmental consideration, organizations can further strengthen their long-term sustainability performance. The green approach focuses on using environmentally conscious methods to reduce adverse environmental impacts and consequently, ecological footprint of manufacturing operations. Lean manufacturing's inherent emphasis on waste elimination across all production stages naturally aligns with green objectives, making it highly adaptable to environmental integration (Gholami et al., 2021).

Key objectives of Green Lean include:

- Reducing ecological footprints.
- Minimizing waste and emissions.
- Improving sustainable manufacturing practices.

Gholami et al. (2021) emphasize that Lean methodologies complement green practices by prioritizing process efficiency and resource optimization. This synergy supports the integration of environmental sustainability into Lean Six Sigma strategies, further enhancing operational and ecological outcomes.

2.7. Integration of Green Lean Six Sigma (GLSS)

Green Lean Six Sigma is an eco-friendly approach that integrates Lean, Green, and Six Sigma principles. Unlike traditional Lean Six Sigma (LSS), which primarily targets production efficiency and quality, GLSS extends these goals by addressing environmental waste and sustainability performance. While Lean focuses on waste elimination and Six Sigma emphasizes process variation reduction, their integration within GLSS supports both operational and ecological improvement (Psarommatis et al., 2020).

Green Lean Six Sigma (GLSS) is a sustainable development approach that leads to improved productivity and profitability through the reduction of wastes, defects and environmental emissions. It represents the convergence of three improvement methodologies—green technology, Lean production, and Six Sigma into a unified framework for sustainable development (Kaswan et al., 2023).

Huang et al. (2023) demonstrate how Lean Six Sigma (LSS), when combined with data-driven decision-making, not only boosts process efficiency but also improve environmental sustainability. Their research shows that by analyzing data on resource use and waste generation, companies can better manage materials and energy, ultimately lowering their environmental footprint. This supports the relevance of GLSS for manufacturing sectors like Ethiopian steel, where structured problem-solving and sustainability is critical.

Sreedharan and Raju (2024) offer valuable insights into the flexibility of Green Lean Six Sigma (GLSS) by examining its application in the food industry. Their systematic review shows that integrating Lean, Six Sigma and Green practices can help companies achieve multiple goals at once improving product quality, enhancing process efficiency, and reducing environmental impact. They also emphasize that successful implementation depends heavily on factors such as strong leadership, employee engagement, and a company culture that supports continuous improvement. Notably, the study highlights how digital technologies and Industry 4.0 tools like IoT and data analytics are increasingly being used to support GLSS initiatives. Although their focus is on the food sector, the challenges and solutions they outline such as balancing efficiency with sustainability are just as relevant to other industries, including steel manufacturing. This makes their findings highly applicable to the current study, which aims to apply GLSS principles at Walia Steel Industry to address issues like high defect rates, material waste, and inefficient resource use.

Gandhi and Thanki (2024) expand the GLSS framework by introducing a Sustainability Index tailored to SMEs. Their framework integrates Lean, Green, and Six Sigma methodologies into a unified measurement tool that assesses environmental, economic, and social performance indicators aligning well with the triple bottom line concept of sustainability. The index designed to not only monitor but also improve the sustainability efforts of organizations through a systematic, data-driven approach. One of the most notable aspects of their work is the development of a prioritization matrix that identifies key performance areas in which manufacturers can maximize impact through the GLSS framework. These areas include resource efficiency, waste reduction, defect minimization, stakeholder engagement, and long-term profitability. Their research demonstrates that when implemented strategically, GLSS can create a positive ripple effect across the entire value chain, promoting eco-efficiency and operational excellence simultaneously.

Recent studies have emphasized the growing relevance of Green Lean Six Sigma (GLSS) as an integrated framework for improving operational efficiency and environmental performance across various manufacturing sectors. Jabbour, Jabbour, and Godinho Filho (2020) conducted a systematic review focusing on small and medium-sized enterprises (SMEs), revealing that GLSS can significantly support sustainability goals even in resource-constrained environments. Their findings highlight that leadership commitment, workforce involvement, and continuous improvement culture are critical for successful implementation. Complementing this, Salgado, Mello, and Silva (2021) explored how the maturity level of an organization’s quality management system influences GLSS success. Their research, based on Latin American manufacturers, found that firms with more developed quality infrastructures achieved greater benefits in defect reduction and environmental improvements, reinforcing the need for a solid foundation in quality practices especially in developing countries like Ethiopia.

Furthermore, Mourtzis, Angelopoulos, and Panopoulos (2022) applied a GLSS-based model specifically to defect reduction in metal manufacturing. Their study demonstrated measurable improvements in process performance, material efficiency, and waste reduction through simulation and real-world application. These findings directly support the approach of the current study, which aims to implement GLSS at Walia Steel Industry to address quality issues, reduce environmental waste, and enhance sustainable manufacturing outcomes.

In the context of developing countries like Ethiopia, where industries such as steel manufacturing face high operational costs, limited technical expertise, and increasing pressure to adopt sustainable practices, this model offers actionable insights. The Sustainability Index developed by Gandhi and Thanki (2024) could serve as a benchmarking and performance evaluation tool for Ethiopian steel companies aiming to integrate sustainability into their quality improvement strategies. The findings emphasize that GLSS not only contributes to operational improvement but also fosters a culture of continuous improvement, employee participation, and environmentally responsible production. Incorporating such structured tools into Ethiopian manufacturing could bridge the current implementation gaps and serve as a stepping-stone toward industry-wide transformation.

Moreover, several confirm that the integration of Lean and Six Sigma under the umbrella of Lean Six Sigma (LSS), which aims to enhance both environmental and operational performance while maximizing profitability and competitiveness. Among the various Lean applications, MFA has become a vital tool for improving environmental and operational outcomes, due to its effectiveness in tracking waste and resource efficiency ease of use.

Organizations practicing Green Lean have proactively adopted environmentally conscious measures to promote cleaner manufacturing. These programs not only promote the production of eco-friendly products but also focus on minimizing the ecological impact of production. As a result, the adoption of green practices has become an established philosophy in modern manufacturing. This strategy not only improves organizational efficiency from an environmental perspective but also reduces the ecological footprint of products and services, all without compromising the financial objectives of the organizations involved (Gholami et al., 2021).

Yadav et al. (2021) developed an integrated model of GLSS that combines Lean, Six Sigma, and Green practices to enhance sustainability, productivity, and defect reduction.

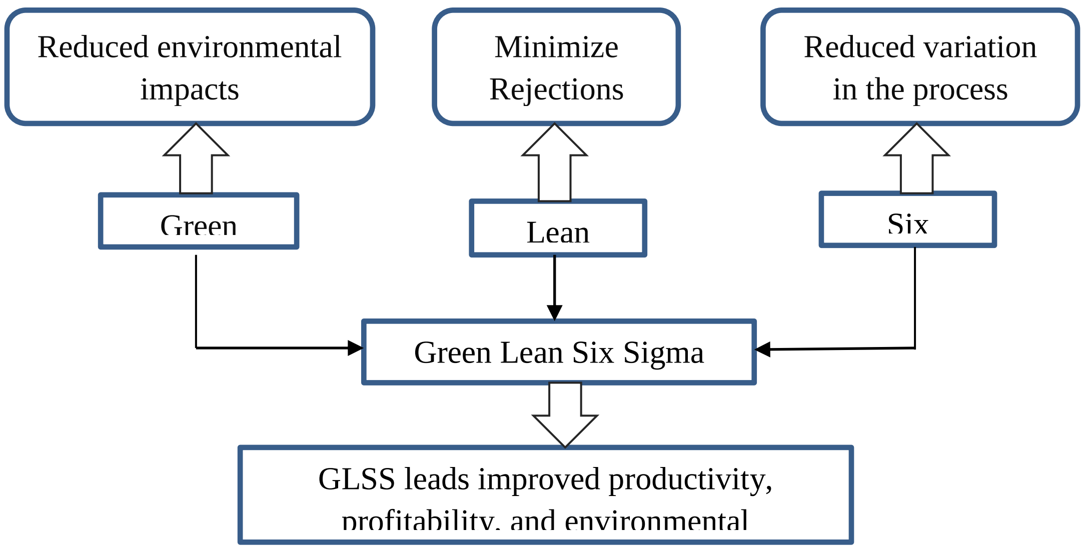


Figure below illustrates an integrated model of GLSS, showing how the synergy among Lean, Green, and Six Sigma leads to enhanced productivity, environmental performance, and profitability:

Figure 2.1: Integrated model of GLSS. Adapted from Yadav et al. (2021)

Singh and Sultan (2019) argue that GLSS fosters cross-functional collaboration and long-term performance optimization.

Strengths of GLSS integration:- Improves quality and environmental performance simultaneously - Enhances cost savings and customer satisfaction - Aligns operational improvement with sustainability goals

Despite its strengths, GLSS integration also has challenges. It requires a cultural shift, cross-disciplinary training, and organizational commitment to both operational excellence and sustainability. Moreover, overlapping toolsets and misalignment in objectives across departments (production vs. environmental compliance) can limit adoption without proper coordination.

2.7.1. Material Flow Analysis (MFA) within the GLSS Framework

The goal of Green Lean Six Sigma (GLSS) closely aligned with Material Flow Analysis (MFA), a critical tool for locating material wastage and assessing environmental burdens in manufacturing systems. MFA supports waste reduction and sustainability-oriented decision-making by enabling industries to visualize, quantify and analyze material flows across production process (Govindan et al., 2015). According to Brunner and Rechberger (2004), MFA is particularly useful for resource conservation and environmental evaluation, as it clarifies the input-output relationships within industrial systems.

Wakjira et al. (2018) highlight how MFA can used to address manufacturing system bottlenecks in Ethiopia, particularly in areas where material losses and inadequate process control are common. In a similar vein, a recent study that traced waste generation and resource consumption trends and was published in the Journal of Cleaner Production (2022) highlights the importance that MFA plays in encouraging sustainable manufacturing methods.

Abebe (2025) further advocates the integration of MFA with digital technologies in Ethiopian industries. According to these observations, MFA not only works well with the GLSS framework but also improves its application in situations where sustainability and productivity are crucial, like Ethiopia's steel profile industry.

2.8. The Need for GLSS in Ethiopian Steel Industry

2.8.1 Industrial Challenges

Ethiopia’s steel profile manufacturing industry faces multiple operational and sustainability challenges, including high material waste, inefficient energy use, quality control issues, and weak regulatory enforcement. Studies indicate that energy inefficiency in Ethiopia's industrial sector, particularly steel production, leads to increased carbon emissions and elevated operational costs (Gebremedhin & Mulatu, 2022). Implementing GLSS principles can address these inefficiencies by optimizing resource use and minimizing environmental impact.

Steel production in Ethiopia, particularly in small- and medium-scale industries, is often plagued by high levels of material wastage. Inefficient resource management increases production costs and contributes to environmental degradation. The absence of waste management systems worsens the situation, as the waste generated not only affects profitability but also increases the ecological footprint of production (Liu et al., 2024). Similarly, energy consumption in Ethiopia's steel manufacturing sector is inefficient. Energy-intensive processes, coupled with outdated technologies and machinery, result in unnecessary energy consumption and higher carbon emissions. This contributes to increased production costs and a negative environmental impact, particularly in the context of global concerns over climate change and the growing need for energy conservation in industrial operations (Mekonnen et al., 2023).

Quality control is another persistent issue in Ethiopian steel manufacturing. Common defects include poor material quality, dimensional inaccuracies, and surface imperfections, which result in high rework rates, increased production costs, and reduced production capacity (Tadesse & Mekonnen, 2022). Additionally, as the global manufacturing sector pivots towards sustainability, Ethiopian steel manufacturers are under increasing pressure to comply with emerging environmental standards. Although Ethiopia has begun to establish environmental policies and standards, regulatory enforcement is limited, and the industry lacks a comprehensive framework leaves many manufacturers unprepared for global market demands (Yitbarek & Tefera, 2024).

Despite the potential benefits of Green Lean Six Sigma (GLSS) to address these challenges, there are significant gaps in the adoption of sustainability practices within the Ethiopian steel industry. Most manufacturers continue to rely on outdated technologies such as inefficient furnaces and manually operated production lines, which hinder efforts to reduce waste and optimize energy use (Beyene & Desta, 2023). Advanced systems like automated monitoring tools, energy-efficient equipment, and real-time analytics are rarely implemented, especially by SMEs.

Additionally, poor waste management persists. Many firms lack infrastructure for proper waste segregation, recycling, or zero-waste strategies leading to high disposal costs and environmental pollution that adversely affect both local communities and broader ecosystems (Hailu & Sisay, 2023).

Financial constraints also serve as a major barrier to the adoption of GLSS, particularly for small and medium-sized enterprises (SMEs). The initial investment required for upgrading machinery, training employees, and acquiring green technologies is often prohibitively high, making it difficult for companies to implement sustainability initiatives, even if they recognize the long-term benefits (Tiruneh & Mekonnen, 2023). Moreover, the lack of a skilled workforce in Ethiopia, capable of managing or leading GLSS initiatives, further hampers the effective implementation of quality improvement and environmental sustainability practices (Abebe & Tadesse, 2024).

Finally, weak regulatory support, including the absence of clear policy frameworks and incentives to encourage the adoption of sustainable manufacturing practices, hinders the progress of Ethiopian steel manufacturers in integrating green technologies and sustainability practices (Tesfaye & Gebremariam, 2023).

2.8.2 Existing Gaps in Sustainability Efforts within Ethiopian Steel Manufacturing

While global industries have made significant progress in adopting Green Lean Six Sigma (GLSS), the Ethiopian steel profile manufacturing sector continues to face critical challenges in implementing structured sustainability frameworks. Limited access to advanced waste management technologies and energy-efficient production systems has contributed to this gap (Tesfaye et al., 2021). Moreover, research indicates that many Ethiopian manufacturers do not fully implement green initiatives due to financial constraints and a lack of technical expertise (Abebe & Bekele, 2020).

Adopting Green Lean methodologies could help address these gaps by providing systematic strategies for waste reduction, defect minimization, and regulatory compliance. However, meaningful adoption requires coordinated efforts among government institutions, industry leaders, and educational bodies. Studies suggest that governments and industry leaders must collaborate to establish incentives, training programs, and investment policies to encourage sustainable practices in Ethiopian manufacturing (Mengesha et al., 2023).

Despite the potential benefits of Green Lean Six Sigma (GLSS), several significant gaps exist in the adoption of sustainability practices within the Ethiopian steel industry. One of the persistent barriers is the limited technological adoption, as many Ethiopian steel manufacturers continue to rely on outdated production technologies that are both energy-intensive and wasteful. Modern technologies, such as energy-efficient furnaces, automated production lines, and real-time monitoring systems, are often either unavailable or unaffordable for smaller manufacturers. This results in companies operating inefficiently, with limited capability to optimize resource usage or reduce waste (Beyene & Desta, 2023). Another key challenge is the lack of advanced waste management systems. Ethiopian steel manufacturers generally lack the infrastructure for effective waste segregation, recycling, and the adoption of zero-waste initiatives. Without proper waste management systems, manufacturers face high disposal costs and contribute to environmental pollution, impacting both local communities and the global environment (Hailu & Sisay, 2023). Additionally, financial constraints pose a significant obstacle to implementing GLSS in Ethiopia's steel industry. Many small and medium-sized enterprises (SMEs) lack the necessary capital to invest in upgrading machinery, training employees, and acquiring green technologies. The high initial investment required to implement GLSS often prevents companies from pursuing sustainability initiatives, despite recognizing the long-term benefits of such practices (Tiruneh & Mekonnen, 2023). The lack of a skilled workforce further complicates the adoption of GLSS, as the implementation of these methodologies requires a workforce trained in both quality management and environmental sustainability practices. However, Ethiopia faces a shortage of personnel with the expertise necessary to lead or manage GLSS initiatives, hindering manufacturers’ ability to effectively integrate green technologies and quality improvement processes into their operations (Abebe & Tadesse, 2024).

Finally, weak regulatory support presents another challenge. Although Ethiopia has made progress in improving environmental regulations, the enforcement of these policies remains weak. There is a lack of clear policy frameworks and incentives to encourage the adoption of sustainable manufacturing practices. This regulatory gap hinders the progress of Ethiopian steel manufacturers in adopting green technologies and sustainable practices, limiting the industry’s overall sustainability efforts (Tesfaye & Gebremariam, 2023).

2.8.3. How GLSS Can Address These Gaps

Green Lean Six Sigma (GLSS) offers a promising solution to address the existing key challenges in Ethiopia steel manufacturing industry by integrating Lean Manufacturing waste-reduction techniques with Six Sigma process improvement focus, all embedding environmental sustainability. One of the primary GLSS advantage is its potential to improve waste management and resource efficiency. Tools such as Value Stream Mapping (VSM) and Environmental Value Stream Mapping (EVSM) enable manufacturers to visualize and assess material and energy flows throughout the production processes. This helps identify inefficiencies, reduce unnecessary resource use and minimize waste generation resulting in lower operational costs and a reduced environmental impact (Hoffman et al., 2024). In terms of energy efficiency, GLSS facilitates the optimization of energy consumption by integrating Lean and green practices. Techniques such as process optimization, energy audits, and the use of energy-efficient technologies can help reduce energy usage and carbon emissions, addressing one of the industry's most pressing concerns (Yohannes et al., 2024).

Additionally, GLSS supports defect reduction and quality improvement by applying Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) methodology. Applying DMAIC allows companies to reduce process variability, improve consistency, and minimize product defects—leading to fewer reworks, reduced waste, and lower production costs (Raju & Birehanu, 2023; Ali & Adhikari, 2024).

Finally, GLSS helps manufacturers in complying with both local and global environmental standards by integrating environmental considerations into quality improvement processes. By adopting the environmental sustainability principles of GLSS, Ethiopian steel profile manufacturers can enhance their green initiatives, reduce emissions, and minimize their overall environmental footprint (Hassan et al., 2023). This alignment not only enhances competitiveness but also prepares the industry for participation in environmentally conscious global markets.

2.9. GLSS Applications in Developed vs. Developing Economies

The comparison between global(developed countries) and local (developingcountries) perspectives on sustainable manufacturing practices, particularly in the context of Lean Six Sigma (LSS) and Green Lean Six Sigma (GLSS), reveals distinct challenges and solutions across developed and developing countries, including Ethiopia. While the core principles of GLSS are universally applicable, the challenges and methods to its implementation vary significantly due to differences in infrastructure, technological advancement, regulatory frameworks, and economic conditions.

In developed countries, such as those in Europe and North America, the adoption of GLSS often driven by well-established regulatory frameworks, advanced technologies, and a mature understanding of sustainability. Companies in these regions typically have access to cutting-edge energy-efficient technologies, automated systems, and comprehensive waste management strategies. The major challenges they face tend to revolve around maintaining competitiveness in a saturated market, integrating new green technologies within existing processes, and ensuring compliance with increasingly stringent environmental regulations. For instance, large corporations in these regions may face resistance to change from employees or management who are accustomed to traditional manufacturing processes, which can hinder the successful implementation of GLSS (Bengtsson et al., 2023).

In contrast, developing countries like Ethiopia encounter different sets of barriers when it comes to implementing GLSS. The primary challenges often include limited technological adoption, financial constraints, a lack of skilled workforce, and weak regulatory enforcement. Many Ethiopian steel manufacturers still rely on outdated and inefficient production technologies, which lead to excessive waste, higher energy consumption and emissions (Beyene & Desta, 2023). For small and medium-sized enterprises (SMEs), the initial investment needed to upgrade to energy-efficient technologies or implement structured waste management systems is often unaffordable. Compounding this is the absence of government financial incentives or support mechanisms (Tiruneh & Mekonnen, 2023). Furthermore, there is a shortage of trained professionals, who can manage and implement GLSS practices effectively. The absence of skilled workers makes it difficult for Ethiopian manufacturers to adopt advanced practices like Six Sigma, which require a certain level of expertise (Abebe & Tadesse, 2024).

Regulatory weaknesses further inhibit progress in Ethiopia.. While there are some local environmental policies, the enforcement mechanisms are weak, and there is a lack of clear guidelines to encourage sustainable manufacturing practices. This weak regulatory framework makes it difficult for manufacturers to prioritize environmental concerns, often leading to non-compliance with global standards (Yitbarek & Tefera, 2024). In contrast, developed countries benefit from robust regulatory support that includes tax incentives, subsidies, and penalties for non-compliance, which act as strong drive for businesses to adopt GLSS practices.

Despite these differences, the solution to these challenges lies in tailored approaches that consider the unique constraints of each region. In developed countries, the focus should be on improving the integration of green technologies into traditional manufacturing processes and enhancing employee engagement to overcome resistance to change. For Ethiopia, the key to overcoming barriers such as financial constraints and lack of skilled labor lies in creating accessible funding mechanisms for SMEs, fostering partnerships with international organizations for knowledge transfer, and implementing educational programs to build the necessary workforce (Tesfaye & Gebremariam, 2023). Moreover, Ethiopia could benefit from studying successful global regulatory models and gradually developing a robust policy framework that incentivizes sustainability while ensuring compliance.

In conclusion, while both developed and developing countries face challenges in adopting GLSS, the nature of these barriers and their solutions vary substantially. For Ethiopia, addressing the technological limitations, financial constraints, and regulatory challenges will be essential to promote successfully implementation of GLSS and fostering a more sustainable steel manufacturing industry. Exploring local case studies and data further can help to provide concrete examples of how GLSS can effectively applied in the Ethiopian context.

Generally, In developed countries, GLSS implementation often leverages automation, advanced analytics, and access to environmental monitoring technologies. Studies (e.g., Psarommatis et al., 2020; Singh & Sultan, 2019) show widespread use in automotive, aerospace, and electronics sectors with sophisticated sustainability tracking.

In contrast, in developing countries, including Ethiopia, GLSS adoption is limited due to resource constraints, lack of data infrastructure, and limited awareness. However, some studies (Gebreyohannes, 2018; Abduljelil, 2008) demonstrate the feasibility of adapting GLSS using simplified tools and locally available data, particularly in manufacturing and food processing.

2.9.1 Successful GLSS Implementations in Steel Manufacturing Worldwide

Globally, leading steel manufacturers have successfully implemented GLSS methodologies to reduce production costs, enhance product quality, and meet sustainability goals. Case studies from China, Germany, and the USA demonstrate that GLSS significantly enhances energy efficiency and waste management. (Dues, Tan, & Lim, 2013). In China, steel manufacturers have achieved up to a 30% reduction in energy consumption through GLSS applications, alongside substantial improvements in waste management practices. These include increased scrap material utilization and reductions in greenhouse gas emissions, contributing to more environmentally responsible production systems (Zhou et al., 2020; Wang et al., 2023).

German steel manufacturers have integrated GLSS within their Industry 4.0 frameworks, combining process optimization with digital technologies such as IoT-based monitoring systems. This has enabled real-time quality control, reduced material losses, and improved predictive maintenance, leading to higher product consistency and efficiency. Furthermore, tools like Failure Mode and Effects Analysis (FMEA) and Statistical Process Control (SPC) have been instrumental in minimizing defects in rolling and casting operations, enhancing overall production reliability (Koch et al., 2022).

In the United States, GLSS has been applied extensively across large-scale steel operations to enhance competitiveness in a globalized market. Companies such as Nucor and U.S. Steel have reported improvements in yield, reduction in downtime, and better alignment with environmental standards through the deployment of cross-functional GLSS teams. These initiatives have not only lowered operational costs but also improved employee engagement and corporate environmental responsibility (Smith & Rodriguez, 2021).

These global examples illustrate the potential of GLSS to transform steel manufacturing by integrating quality, efficiency, and sustainability. While the specific strategies and tools may vary by region, the core principles of waste reduction, process improvement, and environmental stewardship remain consistent and effective across diverse industrial settings.

2.9.2 Identification of Barriers to Adoption in Ethiopia and Theoretical Solutions

Despite the global success of GLSS methodologies, Ethiopia faces significant challenges in adopting these practices. The key barriers identified in the literature include:

- Lack of trained professionals and technical expertise, which limits effective implementation of GLSS tools and processes (Dües et al., 2013).
- High initial investment costs and limited financial incentives hinder the transition toward sustainable manufacturing in Ethiopian industries (Mebratu, 2018).
- Government incentives play a crucial role in promoting green industrialization, yet Ethiopia lacks strong regulatory frameworks and financial support for sustainable manufacturing (Gebremedhin & Mulatu, 2022).

- Resistance to change in traditional manufacturing settings slows the adoption of Lean and sustainable methodologies (Garza-Reyes, 2015).
- Collaboration with international organizations and capacity building programs can help bridge the knowledge gap and accelerate sustainable manufacturing adoption (Kaswan & Rathi, 2020).
- Slow adoption of smart such as automation and real-time monitoring systems, which are critical for supporting GLSS implementation (Kumar et al., 2022).

As discussed in literature, competitiveness in modern manufacturing depends heavily on an organization's ability to consistently meet or exceed customer expectations by delivering high-quality products at low cost, on time, and with minimal environmental impact. Globally, many quality and process improvement challenges in manufacturing have been addressed through structured methodologies such as Lean, Six Sigma, and their green-integrated variants. This study applies GLSS and the DMAIC (Define, Measure, Analyze, Improve, Control) methodology as integrated problem-solving tools suited for the Fourth Industrial Revolution era. These tools were selected due to their proven ability to reduce waste, improve process quality, and support sustainability in industrial operations.

The researches reviewed above showed the global aspects of quality improvement techniques. However, in this study case, it will focus on the current state of our country especially steel hollow section-manufacturing sector. It will study on the impact of LSS DMAIC tools and Green LSS in steel profile manufacturing sector in the selected case company for minimization of defect or rework by collecting the necessary data that helps for the identification of problem, what causes it and its impact on the production quality. This will lead to the prevention base quality control method for reduction of cost, profit maximization and enhanced quality product.

2.10. Literature Review gap and summary

A Although numerous global studies have demonstrated the effectiveness of Green Lean Six Sigma (GLSS) in enhancing product quality, reducing defects, minimizing environmental impacts, and promoting sustainable manufacturing, the existing literature remains heavily concentrated in developed regions such as Europe, North America, and East Asia. These regions benefit from well-established regulatory frameworks, advanced technological infrastructure, and a highly skilled workforce factors that facilitate successful implementation of GLSS methodologies.

In contrast, there is a noticeable lack of empirical research focused on how GLSS can be practically applied within resource-constrained environments, particularly in developing countries like Ethiopia. While some studies have acknowledged the broad challenges facing Ethiopian industries including poor waste management, energy inefficiencies, skills gaps, and weak regulatory enforcement few have provided a structured framework for integrating GLSS tools, especially the DMAIC methodology, into industrial processes. Although individual tools such as Material Flow Analysis (MFA), Environmental Value Stream Mapping (EVSM), and Lean Six Sigma have been studied in isolation, their combined and context-specific application with environmental considerations in Ethiopian manufacturing remains underexplored.

This study aims to fill that gap by applying GLSS tools within the operational context of Walia Steel Industry. It explores how globally recognized quality and sustainability practices can be adapted and made effective in Ethiopian steel manufacturing, thereby contributing to both local industrial advancement and global sustainable development goals.

In conclusion, the literature reviewed in this chapter reflects the growing relevance of integrating Lean, Six Sigma, and environmental sustainability. While Lean Six Sigma (LSS) has demonstrated strong results in improving process efficiency and reducing variability, its environmental extension Green Lean Six Sigma has received limited practical attention in Ethiopia. By addressing these gaps, the current study aims to contribute a structured, context-appropriate GLSS framework that supports quality improvement, environmental responsibility, and sustainable industrial development.

CHAPTER THREE

2. RESEARCH METHODOLOGY

This chapter outlines the research design, approach, and methodology used to address the quality and sustainability challenges identified in the steel hollow section manufacturing process at Walia Steel Industry (WSI). The chapter presents the rationale for selecting the Green Lean Six Sigma (GLSS) framework and explains how the DMAIC methodology, supported by Lean and Green tools, was applied as a structured improvement approach. Special emphasis is placed on identifying and interpreting Lean wastes (TIMWOOD) even in the absence of complete quantitative data for all categories.

3.1. Reseach Approach and Design

The study adopted a mixed-method approach, integrating both qualitative and quantitative research elements to ensure a comprehensive analysis. A case study design was employed, deemed appropriate for conducting an in-depth investigation of a real-world industrial issue within a specific organizational setting. The research focused on Walia Steel Industry’s (WSI) steel hollow section production processes during the 2023/2024 fiscal year. Quantitative data were obtained from internal sources such as defect records, production logs, and performance reports, enabling the identification of patterns and trends in operational performance. Complementing this, qualitative data were gathered through interviews with production and quality control personnel, providing contextual insights into process inefficiencies and root causes of defects. The integration of these data sources facilitated triangulation, enhancing the validity and depth of the findings.

3.2. Justification for Using DMAIC within GLSS Framework

Green Lean Six Sigma (GLSS) is a comprehensive improvement philosophy that integrates Lean's waste elimination, Six Sigma's quality control, and Green Manufacturing's environmental sustainability principles. While GLSS offers a theoretical foundation, this research adopts DMAIC (Define–Measure–Analyze–Improve–Control) as the practical, structured methodology for problem-solving.

DMAIC serves as the operational engine to implement GLSS. Each phase of DMAIC draws on tools from Lean (TIMWOOD, Pareto, 5S), Six Sigma (DPMO, root cause analysis), and Green (Material Flow Analysis, simplified Life Cycle Assessment). This structure allows systematic identification, quantification, and mitigation of defects and environmental waste.

The rationale for using DMAIC includes:

- Its compatibility with real-world industrial quality data
- Its structured nature, suitable for problem definition, root cause identification, and sustainable solution development
- Its proven effectiveness in similar studies globally and in Ethiopia (e.g., Gebreyohannes, 2018; Abduljelil, 2008)

The Lean component of GLSS in this study was addressed by interpreting the causes of defects and inefficiencies through the lens of the seven Lean wastes (TIMWOOD). Although no direct implementation was conducted, qualitative observations and recorded defect data were examined to conceptually identify instances of overproduction, excessive motion, waiting time, and rework (defects). This approach enabled a theoretical but meaningful application of Lean waste reduction principles, even without process intervention.

3.1. Ethical consideration

In this research, the researcher prioritized ethical practices throughout the study. The researcher committed to honest presentation of data, transparency of results and proper citation sources. The study minimized bias and conflict of interest. The goal of the researcher is to act in the best interest of humanity and the community, ensuring my work has a positive impact.

3.2. Result dissemination

The finding of this research is presented to the Addis Ababa Institute of Technology School of Mechanical and Industrial Engineering, and to Walia Steel Industry (WSI). This research paper is an input for other researchers.

3.3. Data Collection

Both primary and secondary data were utilized in this study to ensure a comprehensive and well-rounded analysis. Primary data sources include observations of the production process and interviews with key personnel. In addition secondary data sources different literature, journals, reviews, and reports from the company are referred.

A) Primary Data Collection

1. Observations

Field visits to the case company were conducted to observe quality control techniques, raw material inspections, production processes, and final product evaluations. During these visits, the researcher observed the workflow on the production floor, focusing on the implementation of quality management practices. These observations helped to triangulate data collected from interviews and identify areas for improvement in the overall quality management system.

2. Interviews

To determine the areas to be explored in the factory, a semi-structured interview is developed with key quality and production staff. This approach aimed to gather in-depth insights into the defects encountered in the production process and assess the effectiveness of current quality control practices.

Group Discussion:

After the semi structured interview a group discussion is applied. The major aim of the group discussion is to identify the causes of defective products based on quality data provided by the factory, which contains probable causes, and to determine which of the possible causes the genuine cause is or root cause. Quality and production supervisors and staffs are the center of the discussion.

The interviews focused on validating defect definitions, understanding work routines, and identifying perceived root causes. Although only first guiding questions were initially prepared, interviewees were probed further based on their responses. The small but targeted sample ensured that participants were directly involved in day-to-day operations and quality control activities.

This data was used not to perform a full root cause analysis, but to support and validate findings from technical logs and observational process mapping.

The interviews were conducted in groups, consisting of quality control managers, production workers, and supervisors. This collaborative setting facilitated discussions and allowed participants to share diverse perspectives on the challenges faced.

Structured interviews will be conducted with a group of:

- Quality control managers: - To understand existing quality management and sustainability strategies.
- Production supervisor:- To identify challenges in maintaining both product quality and environmental efficiency.
- Quality and production staffs: To identify the existing internal quality issues

B) Secondary Data Collection

1. Literature Review

A comprehensive literature review of previous studies on quality control and sustainable manufacturing was conducted to enhance the understanding of Green Lean Six Sigma

(GLSS) tools and the DMAIC methodology. This review analyzed various methodologies and tools related to quality control, providing insights into their effectiveness and application. It also aimed to deepen the understanding of the principles of sustainable manufacturing, emphasizing the importance of integrating environmental considerations into production processes. Furthermore, the review explored existing frameworks and dynamic methodologies, particularly focusing on GLSS tools, to identify best practices for enhancing quality and sustainability in manufacturing.

2. Company Records

Documents such as yearly production reports and rejection rates were reviewed to track trends and evaluate past quality and sustainability performance. The yearly production reports were used to analyze trends in production performance, while rejection rates were utilized to evaluate the frequency of product defects and their implications for quality control. Additionally, the environmental impact of these defects was assessed. This data collection provided valuable insights into the company's existing practices and performance in both quality and sustainability.

3.4. Data Analysis

This study employed the DMAIC (Define, Measure, Analyze, Improve, Control) methodology an essential component of the Lean Six Sigma framework to analyze quality and environmental related data collected from Walia Steel Industry. The DMAIC approach provided a structured and systematic framework to identify root causes of defects, quantify material waste, and propose improvement actions aligned with Green Lean principles. Sigma level calculations were used to evaluate process capability.

Define: During the Define phase, annual production performance and recorded defect types by category ensuring clarity in the investigation aims and scope. This directed the improvement focus and the problem to be addressed through a process analysis of the quality of the process. The lean tools to define the problem are Pareto to identify the biggest defect and process map to provide an overview of the whole process, and analyze what is required to meet quality standards. And the general process map of the company is drawn. Applied TIMWOOD conceptually to understand various Lean waste types, even if only "Defects" were measured.

Measure: in this phase Pareto Analysis used to identify the most critical defect types and contributing process lines. DPMO and Sigma Level Calculation were used to assess the overall quality performance. Material Flow Analysis (MFA) quantified material utilization and losses, providing insight into Lean and Green performance. A simplified Life Cycle Assessment (LCA) was conducted to estimate the carbon footprint associated with production scrap waste resulting from internal defects.. Given that Walia Steel Industry (WSI) does not conduct primary steelmaking but is engaged in downstream operations such as cold rolling, slitting, cutting, and coating, the emission factor used was tailored accordingly. These downstream processes are known to produce significantly lower emissions, typically ranging from 0.2 to 0.4 tCO_2 e per ton. The lean tool Pareto chart was further utilized to visually map and pinpoint the processes with the highest defect occurrences. By applying Pareto analysis, the research was able to focus efforts on areas with the greatest impact, effectively prioritizing the most significant defects for improvement.

Analyze: in this phase the causes behind the top three defect types were explored using Fishbone Diagrams and the 5 Whys technique. Although the 5 Whys technique is traditionally a team-based root cause analysis tool, in this study it was applied after data collection as part of the analytical phase. The responses from interviews and group discussions with quality control staff were synthesized to construct 5 Whys chains for the major defect types. This indirect application, based on validated company data and expert interpretation, allowed for deeper systemic root cause identification without requiring real-time team workshops..

Validation of the root causes refers to the process of confirming that the underlying factors or reasons identified as the primary causes of a problem or issue are indeed accurate and factual. It involves collecting data, analyzing evidence, and conducting tests to determine whether the root causes are valid and supported by empirical evidence. Validation of the root causes is an important step in problem-solving and helps ensure that the corrective actions taken are effective in addressing the problem and preventing its recurrence. Additionaly identified non-quantified Lean wastes (Waiting, Motion, Overprocessing) during root cause analysis.

Improve: Analysis informed the formulation of improvement strategies targeting high-priority processes and defects. In this step, 5Why is used for validation of the root causes. In this phase of DMAIC mostly employs lean standard tools for problem solving. During this phase, the researcher restructured the process to ensure optimal resource utilization. This stage includes redesigning a material flow process for the major identified defect by process adding additional process.

Control: While not implemented, the study proposed the development of a monitoring framework with key performance indicators (KPIs) as well as mechanisms to sustain the improvements were also proposed.. Performance monitoring indicators were recommended to ensure that gains in quality and sustainability are maintained over time.

Data analysis will be conducted using tools like Excel, and Visio, ensuring a robust interpretation of findings in relation to production process, quality improvements, and environmental sustainability. Ultimately, this study aimed to significantly enhance environmental performance by minimizing waste generation and defect reduction. By fostering a culture of continuous improvement and aligning practices with sustainable manufacturing principles, the organization will enhance its competitive edge and contribute positively to environmental stewardship and corporate social responsibility. This comprehensive approach will help ensure long-term operational success and sustainability in an increasingly environmentally conscious market.

Table 3.1: Data collection

No.	Types of data collection	Objective	Source of data
1	Observation	To understand and assess actual production processes and material flow process	Steel Profile product production process line
2	Group interview	To explore the root cause of defects, validate observations and gather expert insights	Quality control managers, Production supervisor, and Quality and production staffs
3	Company recorded data	To analyze historical defect rate, process defects, production performance and factors of root cause of defect types, and describe each production line	Annual production performance, technical and production data collection sheet, production procedure manual, and annual production process defects

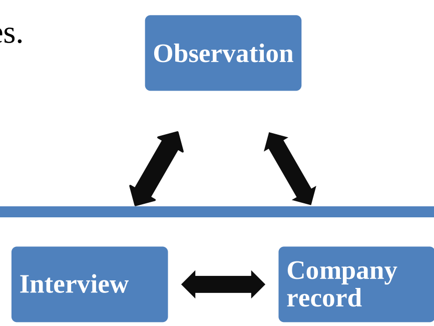
3.5. Sampling Procedures and Technique

The target of the sampling considered Key respondents, such as production supervisor, quality management and production staff, and quality supervisors. These staffs were effectively chosen through the use of purposeful sampling. This non-probability sampling technique was chosen for its efficiency in targeting individuals with relevant knowledge and experience, helping to save both time and resources. Respondents were selected based on their accessibility and availability, as they were often in positions to provide valuable insights during the research. A total of six participants were purposively selected from key functional roles within Walia Steel Industry. These included: one quality control manager, one production supervisor, two production staff, and two quality staff . All participants were directly involved in daily production operations. Their insights were gathered through semi-structured interviews and follow-up validation discussions, providing in-depth understanding of both technical issues and process-level challenges.

3.6 Data Reliability and Validity

When conducting a study that employs primary data observation and company records, establishing reliability and validity is crucial for ensuring credible results. Primary data observation allows researchers to gather firsthand information in real-time, enhancing reliability through consistent data collection practices. By observing processes directly, researchers can minimize biases and inaccuracies that may arise from secondary data sources. Additionally, company records provide a historical context and quantitative data that can further support findings, contributing to the overall reliability of the study. To enhance validity, integrating the 5 Whys method through structured interviews serves as an effective strategy. This method encouraged participants to delve deeper into their responses, allowing researchers to verify the accuracy of observed behaviors and documented records.

Utilizing a triangulation methodology strengthen the reliability and validity of the research. By integrating multiple data collection methods such as direct observations, company records, and interviews using the 5 Whys researchers will be able to cross-verify findings across different sources. This triangulation allowed for a more comprehensive understanding of the research studied, as it will mitigate biases inherent in any single method. Ultimately, this multi-faceted approach enhances both the reliability and validity of the research, leading to more robust conclusions and actionable recommendations for the organization. By ensuring that findings are corroborated through various methods, researchers can provide a more nuanced and accurate representation of the study's focus, thereby improving the overall quality and credibility of the research outcomes.



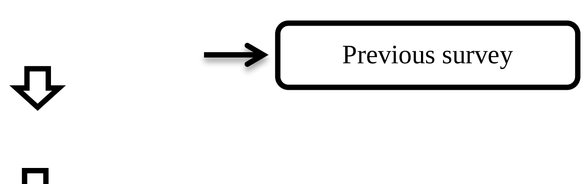
No	Tool /	Inputs for Analysis	Purpose	DMAIC	GLSS

Figure 3.1: Triangualtion method

Table 3.2.: Analysis Tools Used For The Reseach

	Technique			Phase	Category
1	Process Mapping	Production flow, defect logs, expert observations	Define defect-prone stages and value streams	Define	Lean
2	TIMWOOD	defect logs, expert observations	conceptually assess Lean wastes	Define & Analyze	Lean
3	Pareto Analysis	Annual defect data from production records	Prioritize critical defect types (80/20 rule)	Measure	Six Sigma
4	DPMO & Sigma Level	Defect counts, units produced, opportunity per unit	Assess process capability and variation	Measure	Six Sigma
5	Material Flow Analysis (MFA)	Raw material input, finished goods, defect-related scrap	Quantify material input/output, calculate waste	Measure	Green + Lean
6	Fishbone Diagram	Interview insights, technical documents, defect trends	Identify root causes of prioritized defects	Analyze	Six Sigma + Lean
7	5 Whys	Interview answers, maintenance logs, observational data	Explore deeper systemic causes	Analyze	Six Sigma
8	Simplified LCA	Scrap weight, emission factor from literature (0.3 tCO_2 e/t)	Estimate environmental impact of material loss	Analyze	Green
9	SOP and process Redesign	Observed inefficiencies, current SOPs	Propose process improvements (reduce rework, scrap)	Improve	Lean + Green
10	Visual Controls / Audit Plan	Suggested KPIs, training needs, inspection frequency	Build sustainability and quality control mechanisms	Control	Lean + Green + Six Sigma

3.6. Methodological Framework



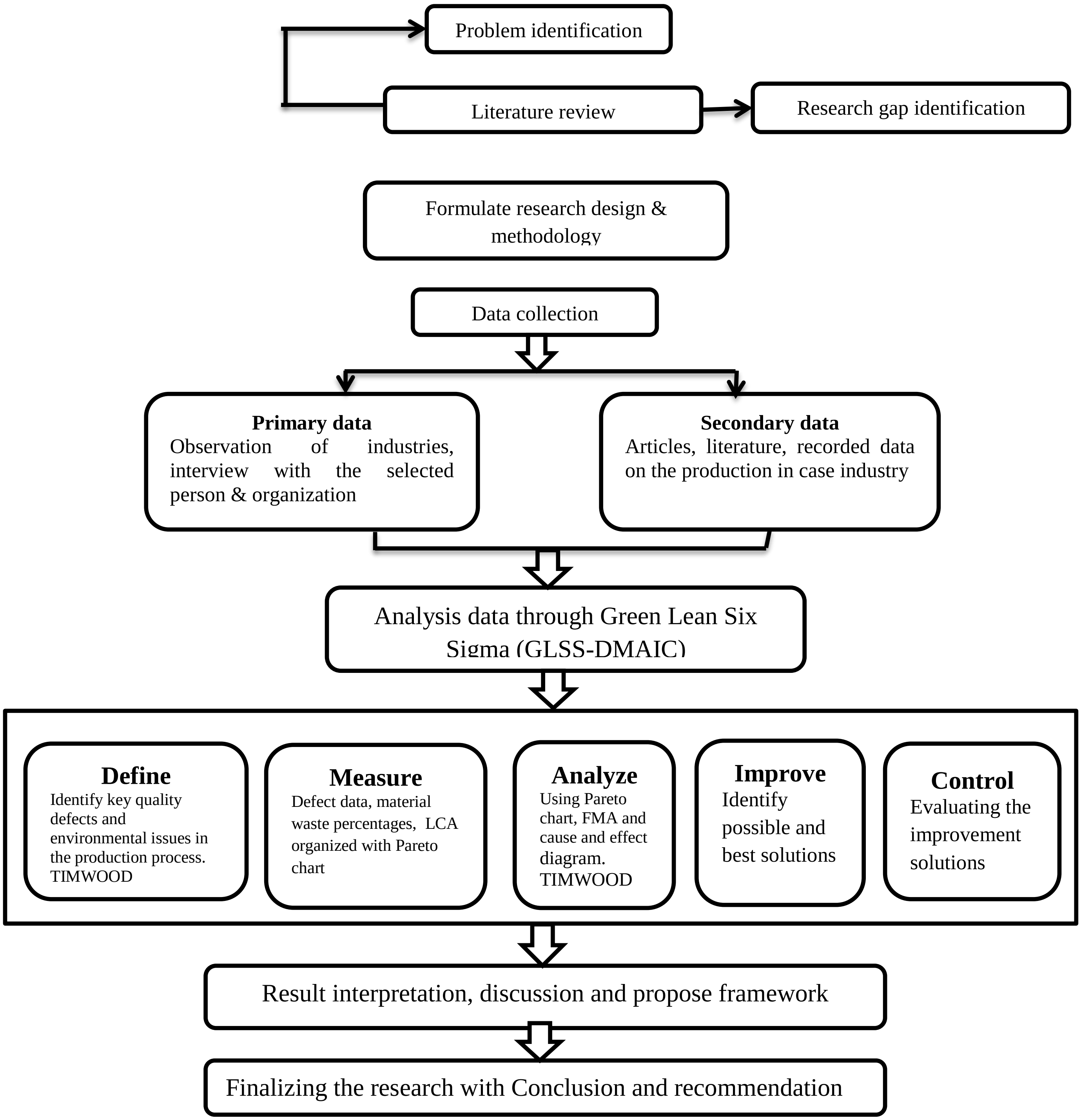


Figure 3.2: Methodological framework

CHAPTER FOUR

DATA PRESENTATION AND ANANLYSIS

This chapter presents the company overview, collected data and investigated using the DMAIC approach and the Green Lean Six Sigma (GLSS) framework. To pinpoint important issue areas, tools like Material Flow Analysis (MFA), Simplified Life Cycle Assessment (LCA), Fishbone diagrams, Pareto charts and TIMWOOD lens are employed.

4.1 Walia steel industry (WSI) overview

Among the different sectors which contribute to fast development of Ethiopian economy is the metal & engineering industry which is the basis for the country's future economic development. The growth of this sector is above any other sector as export led and import substituting industries are given particular priority in the country. Walia Steel Industry has rapidly reshaped Ethiopia's Steel sector and taken initiative that will expand its operation to the wider African market.

Walia Steel Industry (WSI) is a private limited company established in 2006 at Alemgena town of Oromia Regional State, 20km away from Addis Ababa. It was established with an initial capital of Birr 200,000,000 and, in the years to follow, increased the capital to Birr 349,000,000. The Company was established with the objective of manufacturing & marketing of steel products. The industry is built on a total land area of 53,000 square meters of land and currently secured a 100,000 m2 land for expansion and backward integration.

With the aim of alleviating the acute shortage of construction materials in Ethiopia and supporting the national endeavor toward economic development, this initiative also contributes to addressing social challenges by creating job opportunities for citizens. The growth of this sector is above any other sector as export led and import substituting Industries are given particular priority in the country.

The organizational structure depicted in the flowchart illustrates a comprehensive hierarchy within the company, highlighting the key departments and their relationships under the leadership of the Managing Director. At the top, the General Manager oversees various functions, ensuring alignment with organizational goals.

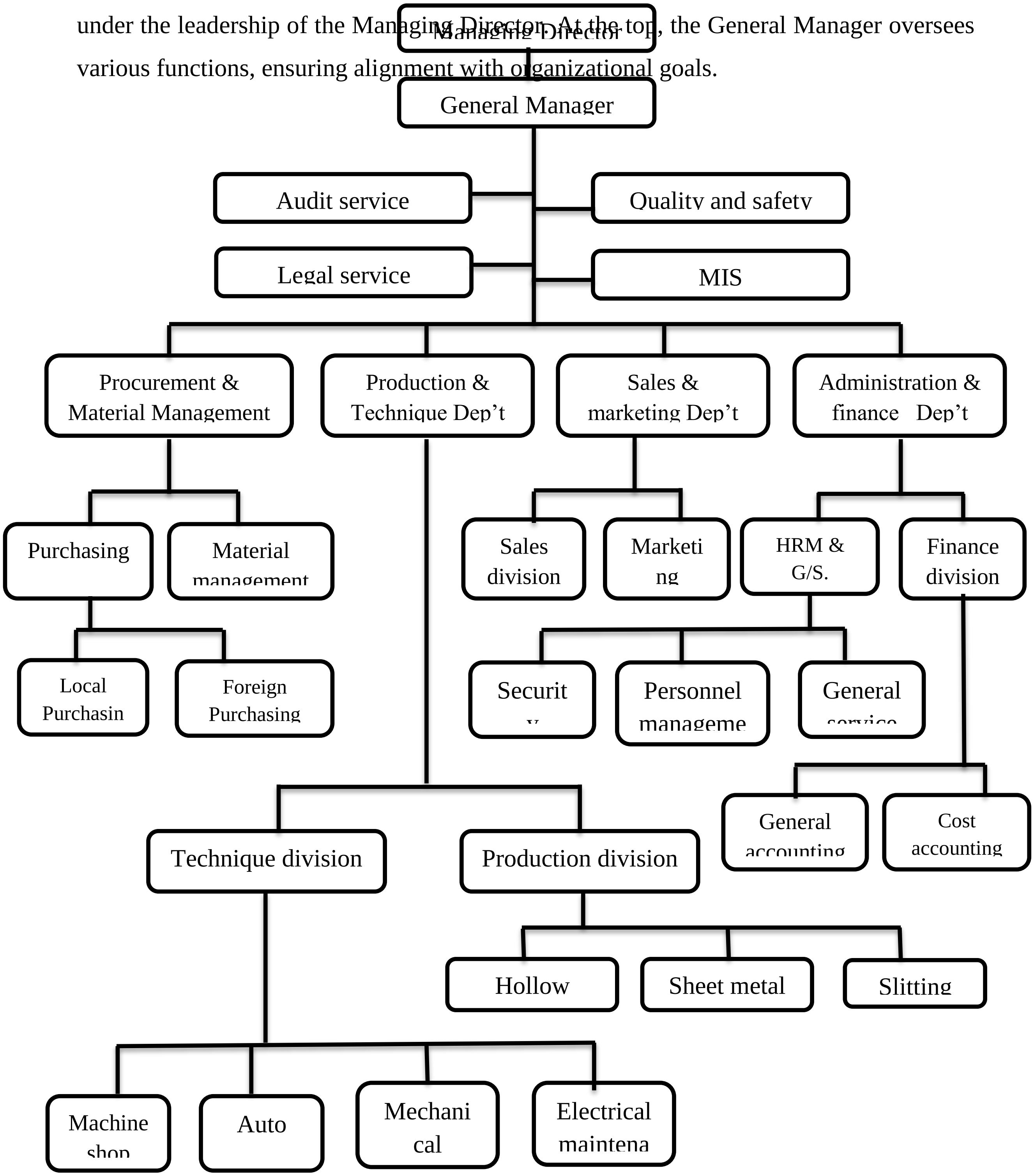


Figure 4.1: Organization structure

The Audit Service and Legal Service departments provide essential support, focusing on compliance and risk management. Below them, the Quality & Safety Service and MIS (Management Information System) departments play vital roles in maintaining product standards and facilitating data-driven decision-making. The Procurement & Material Management Department is crucial for sourcing and managing materials, subdivided into Purchasing, which includes Local Purchasing and Foreign Purchasing. This division ensures that the company can obtain necessary resources efficiently and cost-effectively.

The Production & Technique Division encompasses several key areas: the Production Division focuses on manufacturing processes, while the Technique Division is responsible for technical operations, including machine shop and mechanical maintenance. These divisions are essential for optimizing production efficiency and ensuring equipment reliability. The Sales & Marketing Department is structured to drive revenue, with dedicated teams for Sales and Marketing Division. This separation allows for targeted strategies to enhance customer engagement and market penetration. Additionally, the Administration and Finance Department, alongside HRM & Administration, ensures the smooth operation of internal functions, including financial management and human resources, which are vital for maintaining a productive workforce.

4.2 Data Analysis

The DMAIC approach, as mentioned in the methodology session, is a prominent methodology that many researchers used in Lean Six Sigma. Based on the literature investigated that is directly linked to the case of this research, reviewed each one based on its methodological approach and objective. DMAIC road map used to address the issues in the scenario under consideration.

A) Define Phase – Problem Identification and Defect Overview

Overview of Product Categories at Walia Steel Industry (WSI)

Walia Steel Industry (WSI) manufactures a diverse range of structural steel products that are essential for construction and industrial applications. The main product categories include Circular Hollow Sections (CHS), Rectangular Hollow Sections (RHS), Square Hollow Sections (SHS), and Angle Steel Profiles (LTZ). These hollow sections are commonly used in the fabrication of building frameworks, bridges, pipelines, and machinery due to their strength, durability, and versatility. CHS are preferred for applications requiring uniform stress distribution and torsional strength, such as columns and transmission towers. RHS and SHS offer flat surfaces and consistent geometry, making them ideal for welded structures, frames, and supports. LTZ profiles, which include L-, T-, and Z-shaped angles, are typically used in bracing and connection systems. Assessing the production performance of these four product types provides valuable insight into operational efficiency, material utilization, and areas for improvement within the manufacturing process.

Annual Production Performance Analysis (2023/24)

The table provides a comparison between the planned, actual, and previous year's production figures for four product types: CHS, RHS, SHS, and LTZ. It evaluates each product's performance against both the annual plan and last year's production.

Table 4.1 Annual production performance of 2023/24

S.N	Product Type	Annual plan(Ton)	2023/24 Actual(Ton)	2022/23 Actual (Ton)	Performance in %	
					Yearly	Yearly Against Last
1	CHS	1764.31	596.76	729.72	33.82	-7.54
2	RHS	4561.07	749.86	931.91	16.44	-3.99
3	SHS	9122.14	2260.92	1869.1	24.78	4.30
4	LTZ	982.83	1288.98	0	131.15	131.15
Total		24,998.34	4896.52	5327.71	29.80	-52.48

The provided data outlines the performance of four product types over the year, comparing yearly plans with actual results and last year's figures.

CHS: The planned production was 1,764.31 tons, but the actual production achieved was 596.76 tons, leading to a performance rate of 33.82%. This marks a significant decline of -7.54% compared to last year, indicating challenges in meeting production expectations for this product. The shortfall could be related to raw material issues, equipment downtime, or demand-related constraints.

RHS: For RHS, the target was 4,561.07 tons, with an actual achievement of 749.86 tons, resulting in a performance of only 16.44%. This also reflects a -3.99% drop from the previous year, suggesting persistent issues in achieving efficiency or market delivery for this product type. This area may need process review or capacity assessment.

SHS: In contrast, SHS showed relatively better performance. The planned amount was 9,122.14 tons, while actual production reached 2,260.92 tons, equating to 24.78% of the target. Notably, this represents a growth of 4.30% from last year's performance, indicating an improved operational condition or better market response. This product shows potential for future expansion or focus.

LTZ: LTZ demonstrated the highest performance rate. The planned production was 982.83 tons, but the actual achievement reached 1,288.98 tons, resulting in a performance of 131.15% and a full recovery from 0 tons produced last year. This significant rise may reflect a newly commissioned line or strategic shift in production focus. A notable success deserves further reinforcement.

The total planned production for the year was 24,998.34 tons, with actual production reaching 4,896.52 tons, resulting in an overall performance of 29.80%. This represents a -8.09% decrease compared to the previous year, indicating a general struggle across the board, particularly with CHS and RHS. SHS and LTZ, however, stand out as potential areas for future investment, process improvement, and production strategy development.

Defect Types by Product Category

From reviewing the company technical and production data collection sheet, the main defects identified for each product shown in the table below. It includes types of environmental wastes recorded. The defects listed in Table 4.2 were compiled by synthesizing information from WSI's recorded data. Each defect was categorized based on the terminology used by quality inspectors and supported by field observation of production processes.

Table 4.2: Main Defect Types Recorded

Profile type	Welding defects	Dimension defects	Surface defects	Environmental waste
Circular hollow section (CHS)	Porosity, incomplete fusion	Out-of-specification dimensions	Scratches, corrosion	Material waste from defects; energy use in rework
Lipped channel section (LTZ)	Cracking due to thermal stress	Warping during fabrication	Surface scratches affecting coatings	Scrap from misalignment; emission from processes
Rectangular hollow section(RHS)	Incomplete fusion, cracking	Out-of-specification dimensions	Rust if not treated	Increased waste if not recycled; potential pollution
Square hollow section(SHS)	Porosity, cracking	Out-of-specification dimensions	Rust if corrosion measures are inadequate	Landfill waste from disposal; resource depletion

Source: company recorded data

Each defect type mentioned in Table 4.2 is technically defined as follows:

- Porosity: Small cavities or gas pockets formed during welding due to trapped gases.
- Incomplete Fusion: A weld discontinuity where metal fails to fuse completely, often due to insufficient heat or poor technique.
- Cracking: Fractures formed during or after welding caused by thermal stress or material weaknesses.

- Out-of-Specification Dimensions: Product dimensions falling outside the acceptable tolerance limits set by design standards.
- Warping: Unintended bending or distortion of sections during forming or cooling.
- Scratches: Surface abrasions that affect appearance or compromise coating effectiveness.
- Corrosion: Surface degradation due to chemical or environmental exposure, often from inadequate protection.
- Rust: A specific form of corrosion affecting untreated or exposed steel.

Each hollow section profile produced by Walia Steel Industry, exhibits specific defect trends with varying environmental consequences. Circular Hollow Sections (CHS), Rectangular Hollow Sections (RHS), Square Hollow Sections (SHS), and Lipped Channel Sections (LTZ) all experience critical issues across welding, dimensional accuracy, and surface quality. Welding-related defects such as porosity, cracking, and incomplete fusion are common across all profiles, with LTZ and RHS being particularly susceptible due to thermal stress or poor weld bonding. Dimensional defects, especially out-of-spec measurements, occur frequently in CHS, RHS, and SHS, while LTZ also shows warping during fabrication. Surface-level defects such as scratches, rust, and corrosion affect the final appearance and durability of products; SHS is notably impacted by inadequate corrosion protection, and LTZ experiences coating failures due to surface damage. These quality issues are closely tied to environmental concerns. For instance, rework caused by welding or surface defects leads to material waste and additional energy consumption. Inadequate recycling of RHS scrap increases pollution risk, while defective SHS sections contribute to landfill burden and resource depletion. Thus, controlling these defect types is essential not only for quality improvement but also for achieving sustainability goals under the Green Lean Six Sigma (GLSS) framework.

Key Points on define type of defect

- Welding Defects: Porosity, cracking, and incomplete fusion affect all profiles. LTZ and RHS are more vulnerable due to thermal and bonding issues.

- Dimensional Defects: CHS, RHS, and SHS suffer from out-of-spec dimensions. LTZ shows additional issues like warping during fabrication.
- Surface Defects: is Common across all types including scratches and corrosion. SHS faces rust due to inadequate protective measures. LTZ experiences coating failures from surface imperfections.
- Environmental Impacts: CHS: Material and energy waste from rework. For LTZ, Scrap from misalignment and high emissions. RHS Increased pollution risk if scrap is not recycled. SHS: Disposal leads to landfill waste and resource depletion.

In addition to defining the problem based on product quality defects, this phase also frames the issue through a Lean lens, focusing on non-value-adding activities that contribute to inefficiency. The observed defects such as **porosity**, **incomplete fusion**, **cracking, scratches**, **warping**, **out-of-spec dimensions**, and **corrosion** represent classic examples of Defect waste in Lean manufacturing. These quality failures result in rework, scrap, and increased resource use (energy, labor, and materials), aligning directly with the Lean waste of **Overprocessing**. In some cases, such as **repeated inspections** or **repairs due to surface defects** and **rust,** the process also experiences **Waiting waste**, further reducing overall productivity. Interpreting these defects through the TIMWOOD framework supports a Green Lean Six Sigma (GLSS) approach by linking quality problems with broader process inefficiencies and sustainability implications.

Key findings on define phase

The WSI production process suffers from high defect rates, particularly in CHS and RHS product lines, resulting in:

- Substandard production outputs relative to targets.
- Increased defect rate.

From a Lean perspective, the defects are categorized as:

- **Defect waste**, since they lead to scrap, rework, and reduced first-pass yield.

- **Associated Overprocessing**, due to repeated adjustments, re-welding, or polishing.
- **Waiting waste**, caused by inspection delays and process stoppages for correction or repair.

These findings align with the Define phase of DMAIC, where both quality-critical problems (CTQs) and non-value-adding wastes are identified to prioritize improvement areas.These issues underscore the urgent need to apply Green Lean Six Sigma (GLSS) to systematically identify root causes, reduce variability, and improve both quality and sustainability performance.

B) Measure Phase

The Measure phase at Walia Steel Industry (WSI) focuses on systematically collecting and analyzing data to understand the current performance of the hollow section production process, quantify existing defects, and identify critical areas for improvement. This phase is fundamental for establishing a data-driven baseline before proceeding to root cause analysis.

Sigma level calculation

To further evaluate the quality performance of Walia Steel Industry production process, sigma levels were calculated. Sigma level quantifies the number of defects per million opportunities (DPMO) and provides a standardized measure of process capability in identifying and reducing variation.

Formula

$$DPMO = \frac{total\ number\ of\ defect}{no.of\ produced * opportunities\ per\ defect} \times 1{,}000{,}000$$

To quantitatively assess process capability, the Sigma Level was calculated using the industry-standard Six Sigma approach. This metric expresses the number of defects per million opportunities (DPMO) and converts it into a sigma rating that reflects process performance.

Using WSI's 2023/24 production data:

- Total Products (Tons): 4,896.52
- Total Defects (Tons): 149.83
- Defect Opportunities per Unit: 3

The DPMO calculated here refers to the total defect performance across all product lines. By considering the above assumption, the total amount of defect in the company in major all products is:

$$DPMO = \frac{149.83}{4896.52 \times 3} \times 1{,}000{,}000 \approx 10{,}213$$

Using six sigma table as a reference (see appendix A) this DPMO corresponds to a Sigma Level of approximately **2.6 for without 1.5σ shift** and **3.8 for with 1.5σ shift**. In this scenario, the company's Sigma level is estimated (estimating values between known data points) to be 3.8 with a 1.5 (standard deviation) shift. This indicates a moderately capable process. While better than average in many industrial contexts, it is still significantly below the Six Sigma benchmark of 6. This highlights the potential benefit of further improvement initiatives, particularly under the GLSS framework.

A production process with a current sigma level of about 3.8 is considered reasonably capable, but it still shows a high rate of defects and considerable variability compared to international standards. This outcome emphasizes the importance of structured quality improvement using GLSS techniques. It confirms how crucial it is to apply Green Lean Six Sigma strategically to improve process capabilities and reach international standards.

Process Mapping and Material Flow

The manufacturing process for steel hollow sections at Walia Steel Industry begins with the preparation or request for raw materials. Once the materials are received or issued, they undergo slitting to form strips, which are then fed into the forming section. Depending on the required product, the process continues either with LTZ forming or directly with the circular hollow section (CHS, RHS, SHS) formation. These semi-formed sections are then subjected to fusion welding to join the seams.

After welding, a quality check is conducted to determine whether the weld is acceptable. If the welding is not satisfactory, the section is either adjusted and rechecked or moved directly to reject storage. If the weld is deemed acceptable, the product proceeds to a cooling stage before entering the shaping and sizing section, where it is formed into precise dimensions. Following this, a measurement inspection is conducted to ensure the final dimensions meet the required specifications. If the measurements are not acceptable, the section is moved to reject storage. However, if it passes the measurement inspection, it proceeds to the counting and packing stage before being dispatched to storage.

This linear production sequence represents the material transformation from raw steel input to finished hollow sections, with quality checks and waste handling mechanisms embedded at critical control points. The effectiveness of this process directly impacts the production efficiency, material yield, and defect rates. The table below describes the production procedures using the company's production procedure manual and observations.

The flowchart on the figure 4.2 below outlines a detailed production process for CHS, SHS and RHS and LTZ profiles.

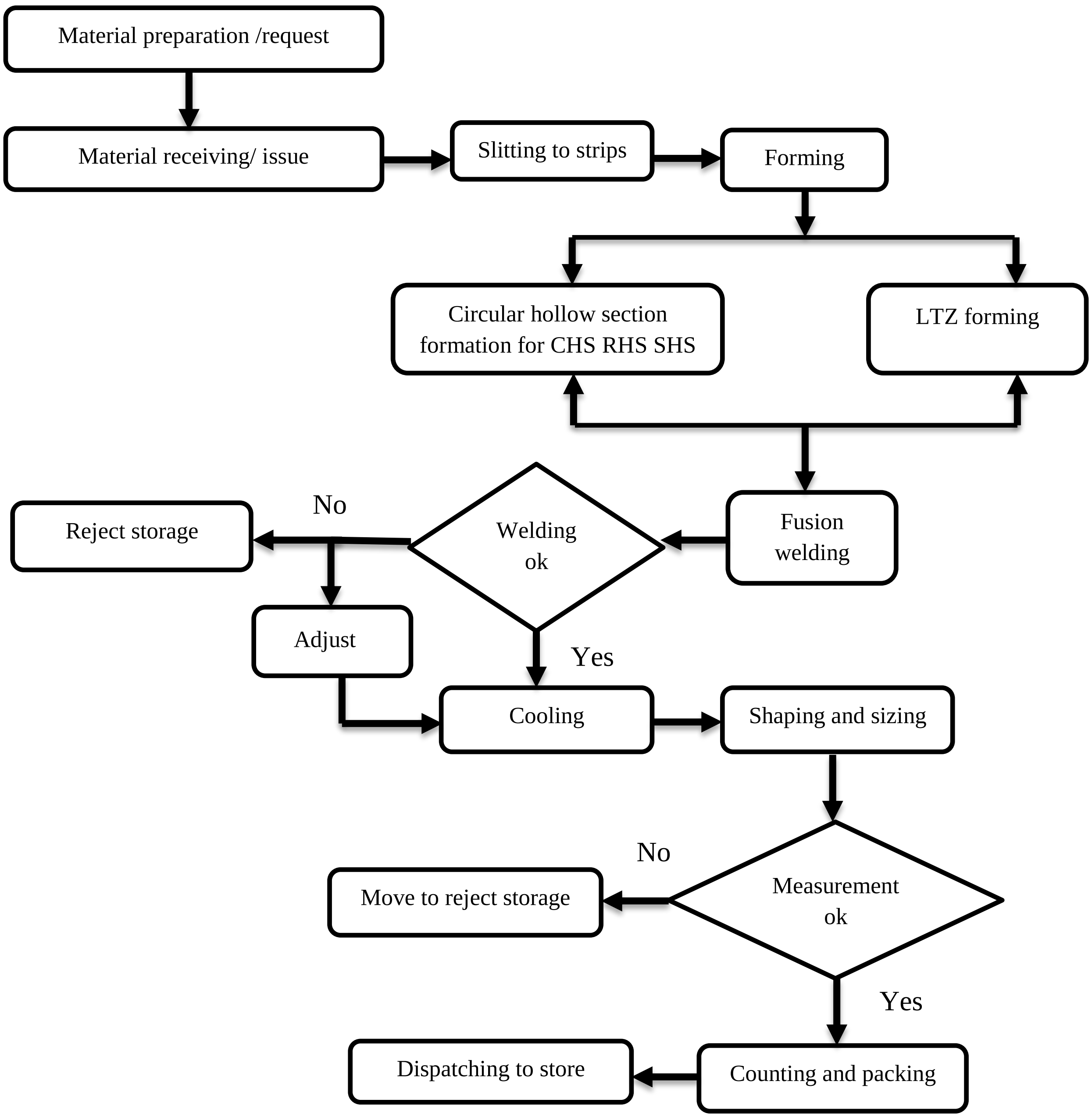


Figure 4.2: General Hollow section production procedure

Table 4.3: Hollow Section Production Process

Process code	Process name	Procedures
line 76(1)	Raw material	Steel coil preparation and receiving
line 200 (1)	Loading	placing steel coils onto the uncoiling machine to initiate the production flow
cut to length-1	Uncoiling and slitting	Cutting coils into strips of required widths using slitters
line 76-2	Strip leveling and inspection	Flattening strips and checking for uniformity, thickness, and surface quality
line 200-2	Loading strip	Feeding leveled strips into the roll forming unit
line 38-1	Roll forming	Gradually forming strips into desired hollow profiles using forming rollers
line 38-2	High frequency welding	Welding the seam using high-frequency current to join the profile
line 38-3	Removing of burrs	Trimming excess weld material (burrs) to ensure clean surface and fit
line 38-4	Water cooling	Cooling the welded profiles to stabilize material properties
line 38-5	Forming	Final profile shaping and dimensional adjustments after welding and cooling
cutting to length -2	Product cutting	Cutting the continuous profile into specified lengths
line 76-3	Inspection	Final inspection for weld integrity, surface finish, and dimensional accuracy

Source: company recorded data

Defect analysis and problem characterization

Using the company recorded annual production process defect data quantitative data analysis was performed to characterize the defects, identify their sources, and assess their impact.

- **Defects by production process:** A Pareto chart analysis revealed that approximately 80% of all reported defects originate from just four distinct processes:

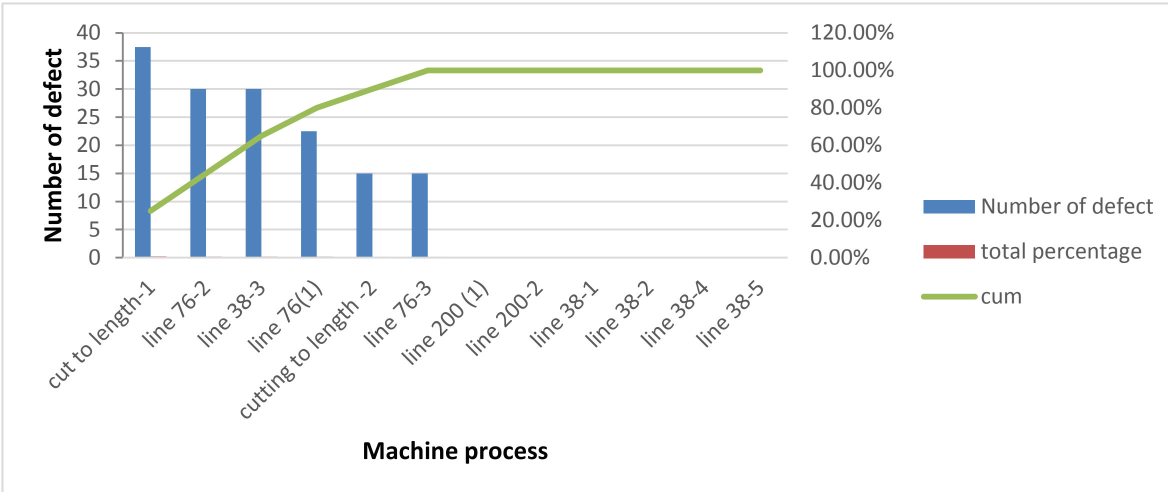


Figure 4.3: Defect by Production Process (Appendix B)

In the above Pareto chart, the "vital few" are the categories that, when addressed, will yield the most significant reduction in overall defects, following the Pareto Principle (80/20 rule). Looking at the cumulative percentage line, the categories that contribute to roughly 80% of the total defects are the vital few.

In this chart, the vital few categories are:

- cut to length-1 (Uncoiling and Slitting)
- line 76-2 (Strip Leveling and Inspection)
- line 38-3 (Removing of Burrs)
- line 76(1) (Raw material)

These four processes collectively account for approximately 80% of all reported defects.

Key Findings of the Chart

"Uncoiling and slitting" is the Primary Defect Source: "cut to length-1" is by far the leading cause of defects, accounting for the highest individual number of occurrences (approx. 37). This indicates a critical bottleneck or consistent problem within this specific process.

Significant Contribution from Post-Cutting Processes: "Strip Leveling and Inspection" (line 76-2) and "Removing of Burrs" (line 38-3) are also major contributors to defects, each with around 30 occurrences. This suggests that issues persist or are created in the immediate steps following initial material processing.

Raw Material Quality is a Concern: "Raw material" (line 76(1)) being among the top four defect categories highlights that the quality of incoming materials is a non-trivial source of problems. Defects at this foundational stage can propagate and cause issues throughout the entire production line.

80% of Defects Stem from Four Processes: Approximately 80% of all reported defects originate from just four distinct processes: Uncoiling/Slitting, Strip Leveling/Inspection, Burr Removal, and Raw Material quality. This strongly validates the application of the Pareto Principle.

Long Tail of Minor Contributors: The remaining processes (e.g., product cutting, inspection, various loading, forming, welding, and cooling steps) individually contribute very few defects. While they add up to the remaining 20% of defects, focusing initial improvement efforts on these would yield significantly less overall impact compared to the top four.

In summary, the chart powerfully demonstrates where to strategically focus resources for quality improvement. The immediate priority should be a deep dive into uncoiling and slitting, strip leveling and inspection, burr removal, and raw material quality to achieve the greatest reduction in overall defects.

- **Prioritizing defect types**

Based on Table 4.2, the main types of defects were categorized along with the corresponding number of defects identified during the annual production total defect 149.83 tons. This categorization provided a clear overview of the specific defect types, allowing for targeted analysis and improvement efforts. By understanding the distribution and frequency of each defect type, the study prioritized areas for intervention and enhances overall production quality focusing on the identified process defects.

This "Pareto diagram" shows the number of defects for each type, sorted from most frequent to least frequent, along with their individual percentages and cumulative percentages. This Pareto analysis on defect types identified the **"vital few" defect types** that collectively account for the majority of overall defects:

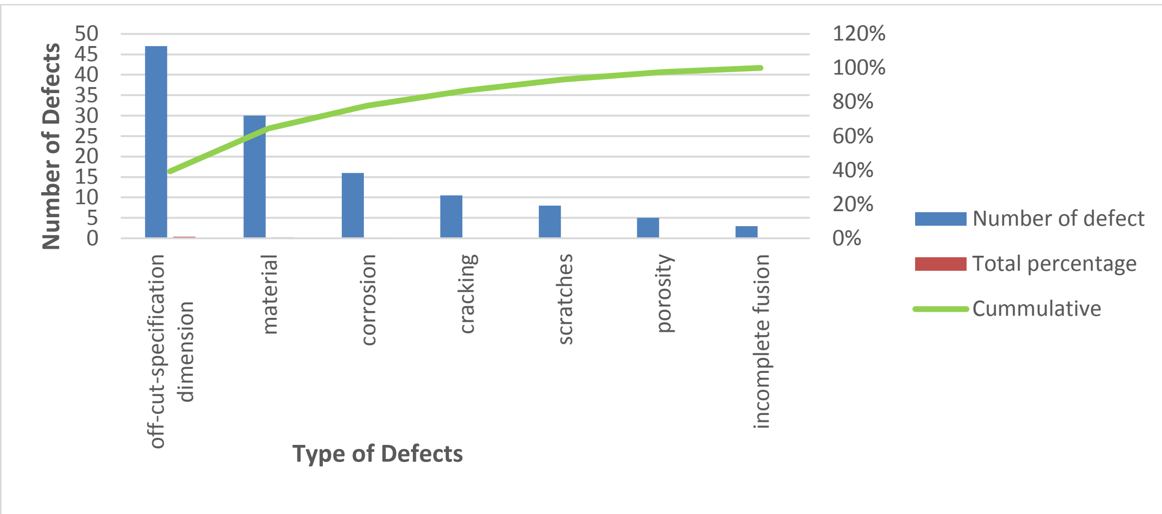


Figure 4.4: Prioritized Defect types for the defect reduction (Appendix C)

Key Findings and the "Vital Few":

Off-cut-specification dimension is the single largest defect type, accounting for 47 defects and representing 39% of all defects. This highlights dimensional accuracy as the most critical area for improvement.

The top two defect types – "Off-cut-specification dimension" and "Material" – collectively account for 64% of all defects (47 + 30 = 77 defects). Addressing these two areas would yield a substantial improvement in overall quality.

The "Vital Few" defects, which comprise approximately 80% of the total, are:

- Off-cut-specification dimension (39%)
- Material (25%)
- Corrosion (13%)

These three defect types sum up to 77% of all defects, effectively representing the "vital few" that, if tackled, would resolve the vast majority of quality issues.

The remaining defects – "Cracking," "Scratches," "Porosity," and "Incomplete Fusion" – make up the remaining 22% of defects. While important, their individual impact is much smaller compared to the top three. For instance, "Incomplete Fusion" is the least frequent defect, with only three occurrences, representing 3% of the total.

Material Flow Analysis (MFA) Findings: An MFA revealed that approximately 2.97 % of input materials are lost due to various defects, equivalent to 149,830 kg. This waste represents both an economic and environmental concern, aligning with Green Lean Six Sigma principles by exposing inefficiencies that affect productivity, raw material consumption, energy use, and waste generation.

Material flow Analysis (MFA)

Material Flow Analysis (MFA) is applied in this phase to assess the material efficiency and waste levels across the hollow section production process at Walia Steel Industry (WSI). By tracing material input, useful output, and defects across product types (CHS, RHS, SHS, LTZ), this tool quantifies where and how much waste occurs. Such quantitative analysis supports the Green Lean Six Sigma (GLSS) philosophy by revealing inefficiencies that affect both productivity and environmental performance.

Material Flow Analysis (MFA) is a vital diagnostic tool for assessing the sustainability, and quality of industrial processes. In the context of hollow section production, MFA enables a systematic evaluation of how raw materials are transformed at each stage of the process—from material preparation, slitting, and hollow formation to welding, sizing, cutting, and final dispatch. By tracking input, output, and losses at every phase, MFA provides critical insights into where value is added and where waste is generated.

According to Walia Steel Industry's 2023/24 production data, 5,046.52 tons of materials including both rejected and final products were used in the hollow section manufacturing process. A material utilization rate of 97.03% was achieved by successfully processing 4,896.52 tons of this total input into finished steel profiles. The remaining 149.83 tons, or 2.97% of the input, were categorized as output that was rejected or faulty. These flaws were mostly caused by surface defects, dimensional errors, and welding-related problems. This breakdown shows the percentage of loss from quality problems, which is a crucial measure for promoting improvements under the Green Lean Six Sigma (GLSS) framework, as well as the overall efficiency of material utilization in the production process.

Table 4.4: Annual Material Flow Summary

	Flow component	**Quantity (ton/year)**	**% of input**	**Description**
1	Raw steel coil	5040	100%	Annual input across all hollow section product lines
2	Finished product output	4890	97.03%	Profiles meet requirement
3	Defect scrap	149.83	2.97%	Lost material due to defects and quality issues

Source: company data

A material utilization rate of 97.03% is found in the Material Flow Analysis based on WSI 2023–2024 production data, with 149.83 tons of material rejected because of different process flaws. According to the GLSS framework, these losses are mostly caused by the four production steps that the Pareto analysis highlighted and emphasizing important areas for process improvement. Even though the usage rate seems high, the total amount of trash is still substantial from an economic and environmental standpoint; therefore, reducing defects is not only a quality objective but also a sustainability requirement.

In this study, MFA was instrumental in highlighting critical loss areas, such as the welding and sizing stages. Targeting improvements in these areas can significantly reduce both operational costs and environmental impacts, aligning perfectly with GLSS principles.

Green waste analysis (Simplified Life Cyle Assessment LCA)

Given that Walia Steel Industry (WSI) does not engage in crude steelmaking but rather performs downstream processes such as coil slitting, shaping, and welding, it is inappropriate to use cradle-to-gate emission factors typical of blast furnace-basic oxygen furnace (BF-BOF) or electric arc furnace (EAF) operations. Instead, this study adopts a more accurate downstream-specific emission factor.

According to the World Steel Association (2022), the average CO_2 e emission for crude steel production via BF-BOF is approximately 1.8–2.0 tCO_2 e/ton. In contrast, downstream processing such as cold rolling, slitting, cutting, or coating generates significantly less carbon emissions, with industry estimates ranging from 0.2 to 0.4 tCO_2 e/ton (Climatiq, 2023; Steelonthenet.com, 2024).

Accordingly, this research applies a conservative emission factor of 0.3 tCO_2 e/ton, consistent with downstream-only operations. Based on WSI's 149.83 tons of annual scrap due to defects, the estimated emissions are approximately 45 tons of CO_2 e/year.

CO2 Impact from processes:

$$\mathbf{149.83} \boldsymbol{tons}/\boldsymbol{year} \times \mathbf{0.3} \boldsymbol{CO_2 e/ton} = \mathbf{45} \boldsymbol{tCO_2 e/year}$$

The calculated 45 tons of CO_2 e per year resulting from defect-related scrap highlights the indirect environmental impact of quality inefficiencies in WSI's downstream operations. While WSI does not emit carbon through steel production itself, the disposal of defective material effectively wastes all embodied resources associated with upstream activities such as mining, hot rolling, and transportation already embedded in the pre-manufactured steel coils. This means that every ton of scrap represents not only lost product value but also avoidable emissions passed through the supply chain.

Therefore, in addition to quality issues, Walia Steel Industry is experiencing increasing environmental impacts due to material defects and production inefficiencies. Each instance of product rework or scrap generation not only contributes to material loss but also results in additional consumption of electricity and operational resources ultimately leading to increased greenhouse gas emissions. Based on simplified Life Cycle Assessment (LCA) using World Steel Association factors (0.3tCO_2 e/ton), the estimated emissions resulting from annual steel scrap waste amount to approximately 45 tons of CO_2 e.

These emissions are indirect consequences of process instability, machinery inefficiencies, and quality failures, indicating a significant environmental footprint tied to defective production. The growing rejection rates from 2.34% in 2022/23 to 3.06% in 2023/24 are not only affecting product quality but also intensifying environmental degradation through increased energy consumption and resource inefficiencies.

Detailed Material Flow and Loss Points for Vital Production Areas

This detailed analysis within the Measure phase provides a comprehensive understanding of where defects occur, their types, and their impact on both production efficiency and environmental sustainability, setting the stage for the subsequent "Analyze" phase of the DMAIC cycle. According to Material flow analysis tool below shows Material Flow Process for each of the four vital production areas identified explain how material moves, where waste is generated, and why each is critical for improvement.

1. **Cut to Length-1 (Uncoiling and Slitting)**

Function: Uncoiling large steel coils and slitting into narrower strips.

Material Loss Points: Coil edge trims discarded, misalignment leading to off-cut material, and damaged edges due to tension or dull blades. (37.5 ton loss due to defect)

Significance: Defects here propagate throughout the entire process, increasing scrap rate and reducing material yield.

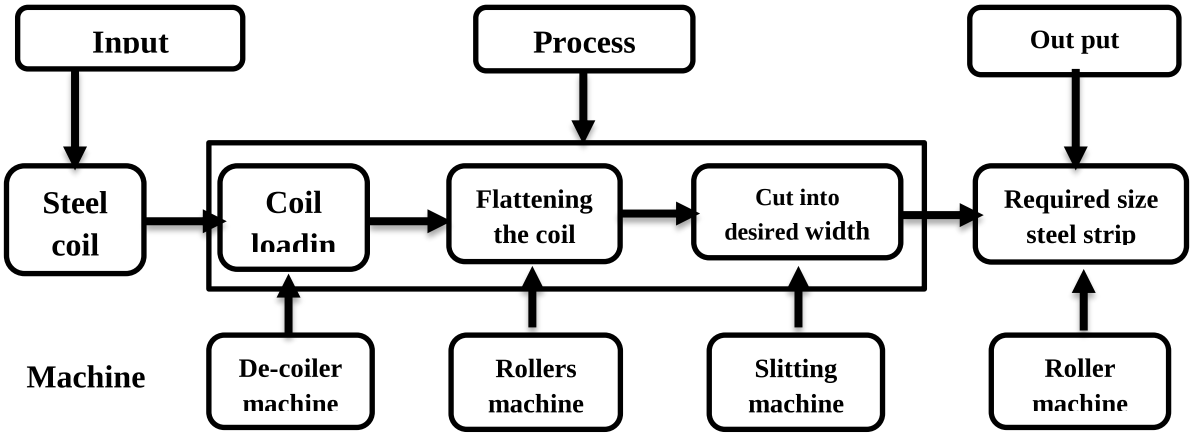


Figure 4.5: slitting and uncoiling material flow

2. Line 76-2 (Strip Leveling and Inspection)

Function: Flattening and inspecting slit strips.

Material Loss Points: Rejection due to surface defects, warped strips or improper tension leading to deviation, and material marked as second-grade due to visual defects. (30 ton loss due to defect)

Significance: Poor leveling affects downstream welding and shaping, and undetected surface defects can lead to structural failures.

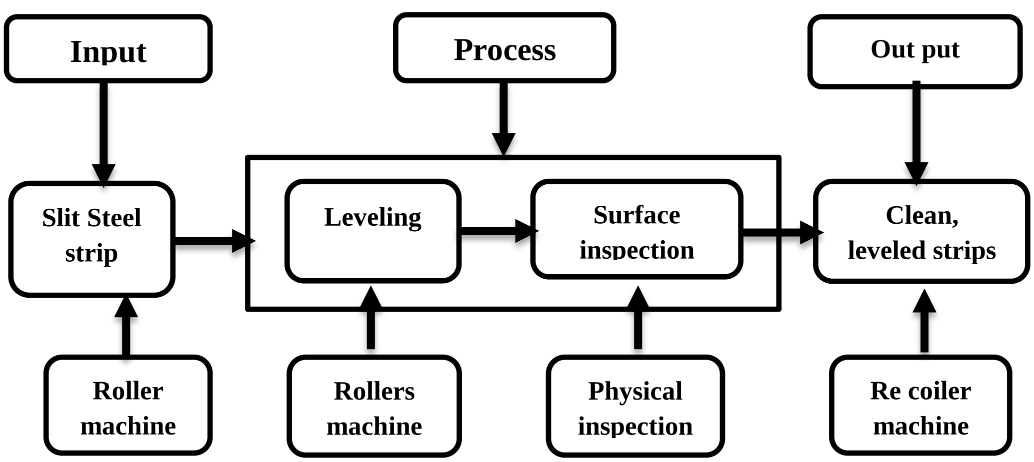


Figure 4.6: Strip Leveling and Inspection material flow

3. Line 38-3 (Removing of Burrs)

Function: Deburring welded steel sections to remove sharp edges.

Material Loss Points: Over-removal reducing pipe wall thickness, improper deburring damaging product edges leading to scrap, and worn tools create inconsistent finishes. (30ton loss due to defect)

Significance: Burrs pose safety issues and affect fit/finish; inefficient deburring increases material loss.

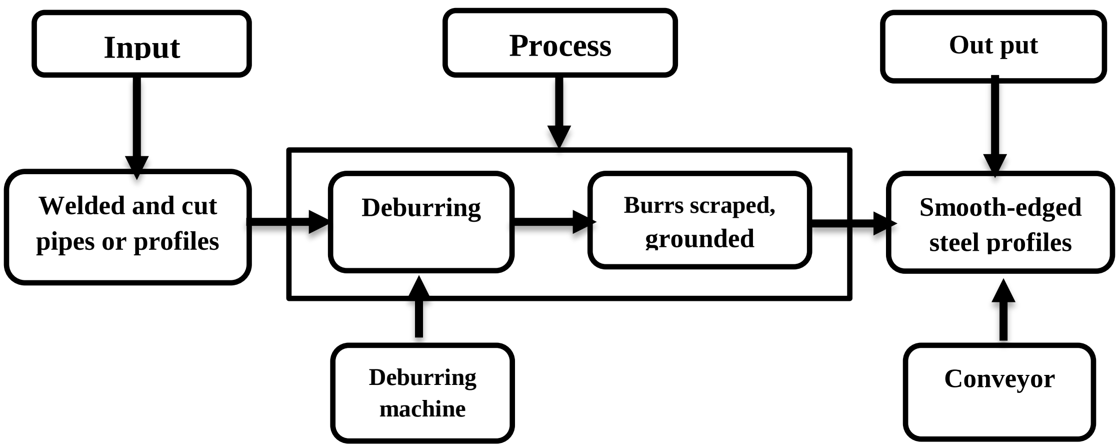


Figure 4.7: Removing of Burrs material flow

4. Line 76(1) (Raw Material Issues)

Function: Receiving raw slit steel and beginning initial shaping or welding.

Material Loss Points: Poor-quality raw material (ripple, stretch marks, cracks), rejection due to non-standard thickness or contamination, and wastage from trimming. (22.5 ton loss due to defect)

Significance: Defects in raw material waste, time and material across all downstream lines and impact weld quality and structural integrity.

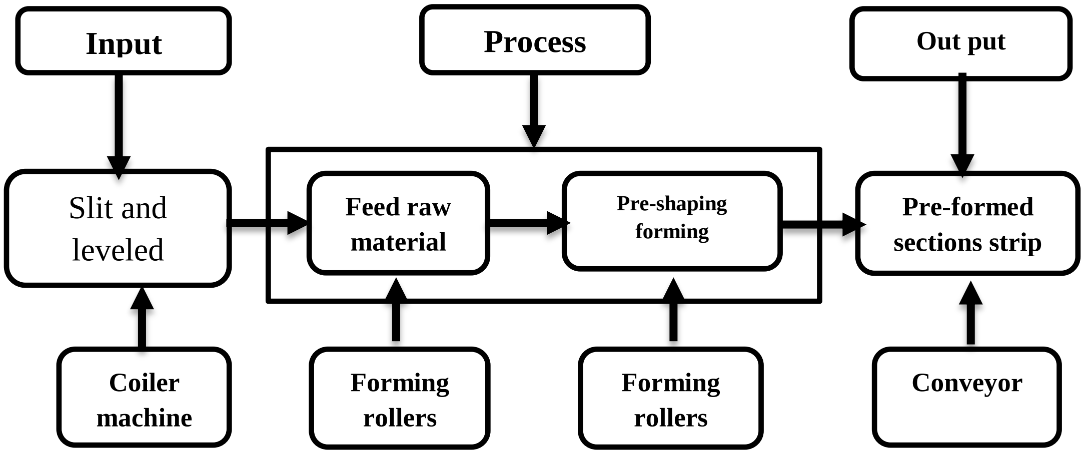


Figure 4.8: Raw Material Issues material flow

This detailed analysis within the Measure phase provides a comprehensive understanding of where defects occur, their types, and their impact on both production efficiency and environmental sustainability, setting the stage for the subsequent "Analyze" phase of the DMAIC cycle.

Although quantitative data were primarily available for Defects, the Material Flow Analysis also indirectly captured potential Overprocessing and Inventory wastes, where rejected or reworked materials accumulated. While not measured numerically, these observations supported a broader Lean interpretation of process inefficiencies through the TIMWOOD framework.

Key findings of the measure phase

- Defect Concentration by Process: 80% of total defects originate from four key production stages:
    - Cut to Length-1 (Uncoiling and Slitting)
    - Line 76-2 (Strip Leveling and Inspection)
    - Line 38-3 (Removing of Burrs)
    - Line 76(1) (Raw Material)

These stages are priority targets for defect reduction based on Pareto analysis.

- Sigma Level Analysis: WSI's current sigma level is approximately **3.8,** based on a **DPMO of ~10.213**.

  - This reflects a moderately capable process, but it falls short of the Six Sigma benchmark, highlighting the need for structured improvement using the GLSS approach.
- Defect Types – The Vital Few: The top three defect types account for 77% of all defects:
  - Off-Cut Specification Dimension (39%)
  - Material-related Defects (25%)
  - Corrosion (13%)

Addressing these will provide the most significant improvement in quality.

- Material Flow Analysis (MFA)
  - **Material utilization rate is 97.03%**, with **2.97% waste (149.83 tons) due to defects**.
  - Waste stems primarily from the same four critical processes, confirming alignment with defect analysis results.
  - MFA confirms the economic and environmental importance of reducing defect-induced waste under the GLSS framework.
- Critical Process Loss Points Identified: Detailed material flow mapping revealed where and how material loss occurs in key processes:
  - Uncoiling/slitting: misalignment, edge trims
  - Strip leveling: surface defects, warping
  - Deburring: over-removal, tool wear
  - Raw material: poor quality, non-compliance
- Green Waste and Environmental Impact (LCA):
  - An estimated 149.83 tons of annual scrap correlates to approximately **45 tons of CO_2 e emissions**, based on global LCA data.
  - Although WSI does not engage in primary steelmaking, it uses pre-manufactured coils that already carry significant embodied carbon.
  - Using a cradle-to-gate approach, the study quantified environmental loss linked to scrap, aligning with the sustainability dimension of GLSS.
- From a Lean (TIMWOOD) perspective, the following waste categories were conceptually identified:

- **Defects**: Quantified directly through rejection rates and quality records.
- **Inventory**: Build-up of defective or rework materials not immediately processed.
- **Overprocessing**: Extra steps to correct dimensional or surface defects.
- These wastes were not all measured numerically, but were observed through production behavior and inferred from process data.

These findings form a solid foundation for the Analyze phase, where root causes behind the prioritized defects and processes will be further explored using Six Sigma and Lean tools.

C) Analyze Phase

The objective of this phase is to find out, validate, and select the root cause for elimination. Root cause analysis identifies a significant number of potential root causes of the company's problems. In this stage the underlying causes of variation and poor performance (defects) identified. The main defect issues of the case company are selected by prioritizing them using a Pareto diagram. Then the selected defect types are off cut specification dimension, material and corrosion. Besides these the other issues that are selected to improve the variation is the process.

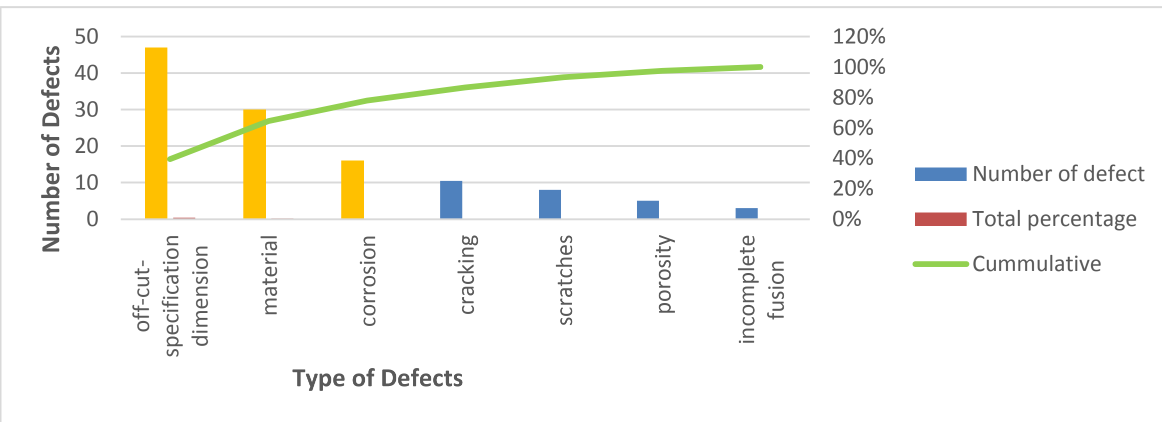


Figure 4.9: The three prioritized defects

Cause and effect /Ishikawa diagram

As shown in figure 4.3 defect-by-process, each prioritized process correlates strongly with at least one of the top three defect types. The root cause analysis was conducted based on the top three defect types; however, these defects were directly linked to the four prioritized process lines identified in the Pareto analysis. While the presentation was organized by defect category, the analysis inherently reflects the prioritized production stages. For instance:

- **Off-Cut Specification Dimensions** were primarily associated with **Cut to Length-1** (Uncoiling and Slitting), contributing **22 tons** of such defects.
- **Material-related Defects** were predominantly observed in **Line 38-3 (Removing of Burrs)** with 17 tons and Line 76(1) (Raw Material Handling) with 13 tons.
- **Corrosion** issues were linked to **Uncoiling and Slitting, Strip Leveling and Inspection, and Raw Material,** with these lines collectively contributing approximately 15.5 tons of corrosion-related defects.

This overlap validates the analytical focus: addressing these three defect categories across these four key process lines provides a comprehensive and strategic intervention plan under the GLSS framework. As such, root cause findings address both defect types and process-specific sources of waste and inefficiency.

To identify the root causes of major defects in hollow section production at Walia Steel Industry, an Ishikawa diagram (also known as a cause-and-effect or fishbone diagram) was used. This tool was applied to analyze the primary sources of defects identified and prioritized in the above figure during the Measure phase Off-cut specification dimension, Material defects and Corrosion.

The causes behind these three major defect types were investigated through reviewing the company technical and production data collection sheet. After collecting and organizing the distributed recorded data, the analysis categorized contributing factors under standard fishbone branches such as Man, Machine, Method, Material, Measurement, and Environment, helping to systematically trace each issue back to its origin.

Here are the specific Cause and Effect (Fishbone) diagrams for each of the three "vital few" defect types identified in your Pareto analysis: Off-cut-specification dimension, Material, and Corrosion.

- **Machine**: Evaluations focused on equipment performance, maintenance schedules, and any mechanical failures that could lead to defects.
- **Method**: The analysis examined the production processes and standard operating procedures to identify inefficiencies or deviations from best practices.
- **Manpower**: Assessments were made regarding staff training, experience, and adherence to quality protocols, recognizing that human error can significantly impact product quality.
- **Raw Material**: The quality of incoming materials was scrutinized to determine if substandard inputs were contributing to production defects.
- **Measurement**: The accuracy and reliability of measurement tools used during production were analyzed to ensure that they provided correct data for quality control assessments.
- **Environment**: Environmental factors, such as temperature and humidity in the production facility, were considered, as they can affect both material properties and equipment performance.

This comprehensive analysis allowed for a clearer understanding of the root causes of quality problems, enabling the study to implement targeted improvements in its operations.

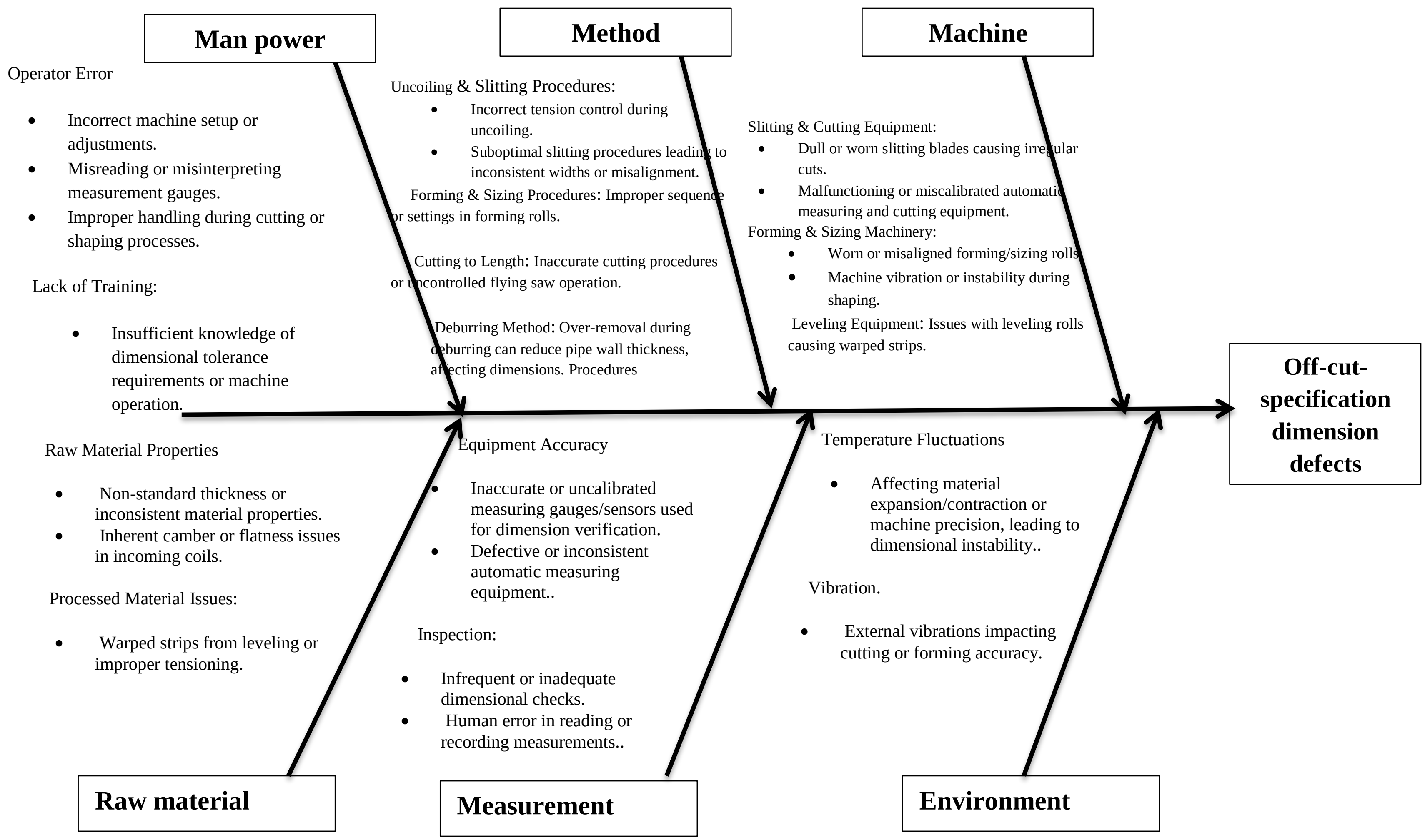


Figure 4.10: Cause and Effect Diagram Off-cut-specification dimension Defects

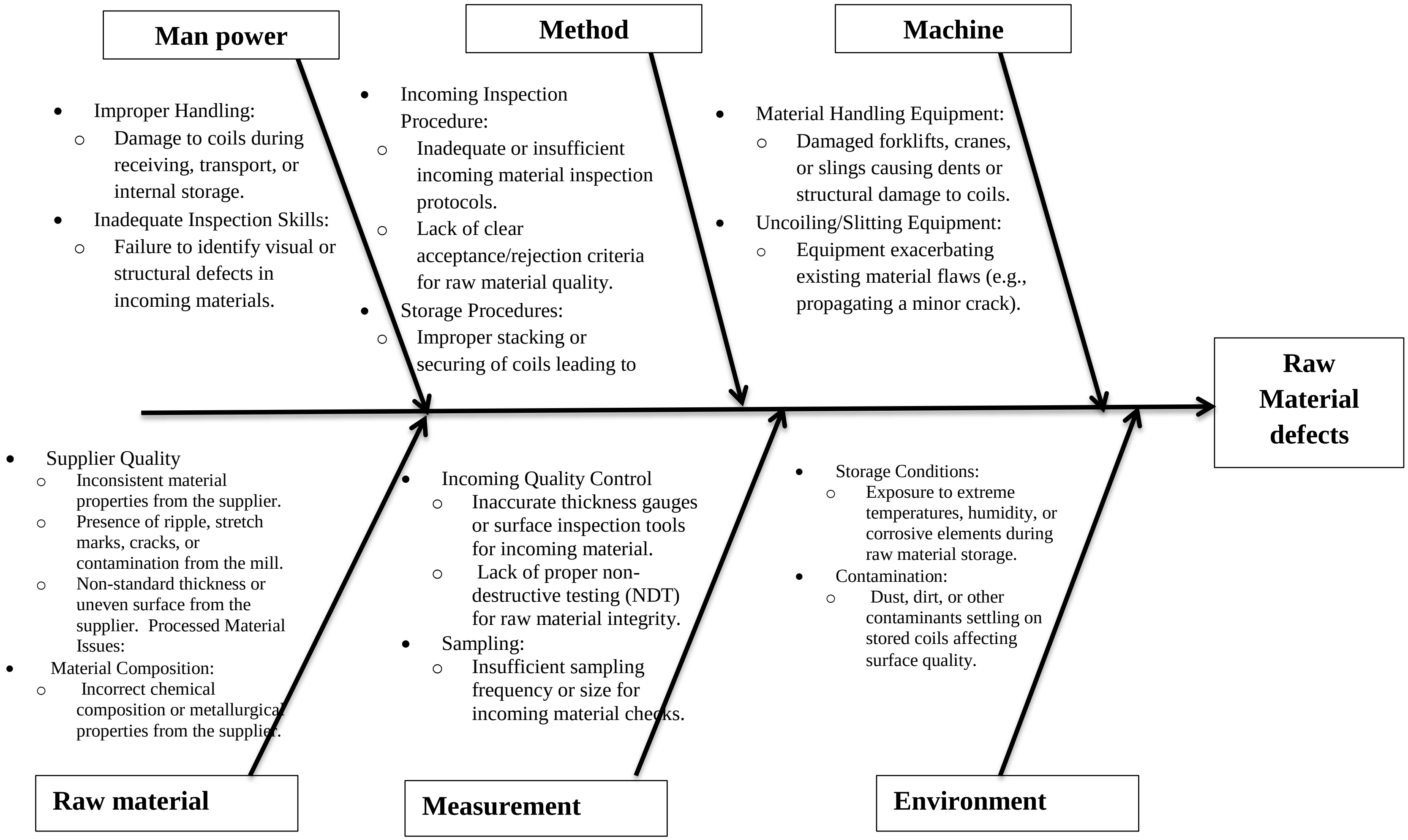


Figure 4.11: Cause and Effect Diagram: Material Defects (Raw Material Issues)

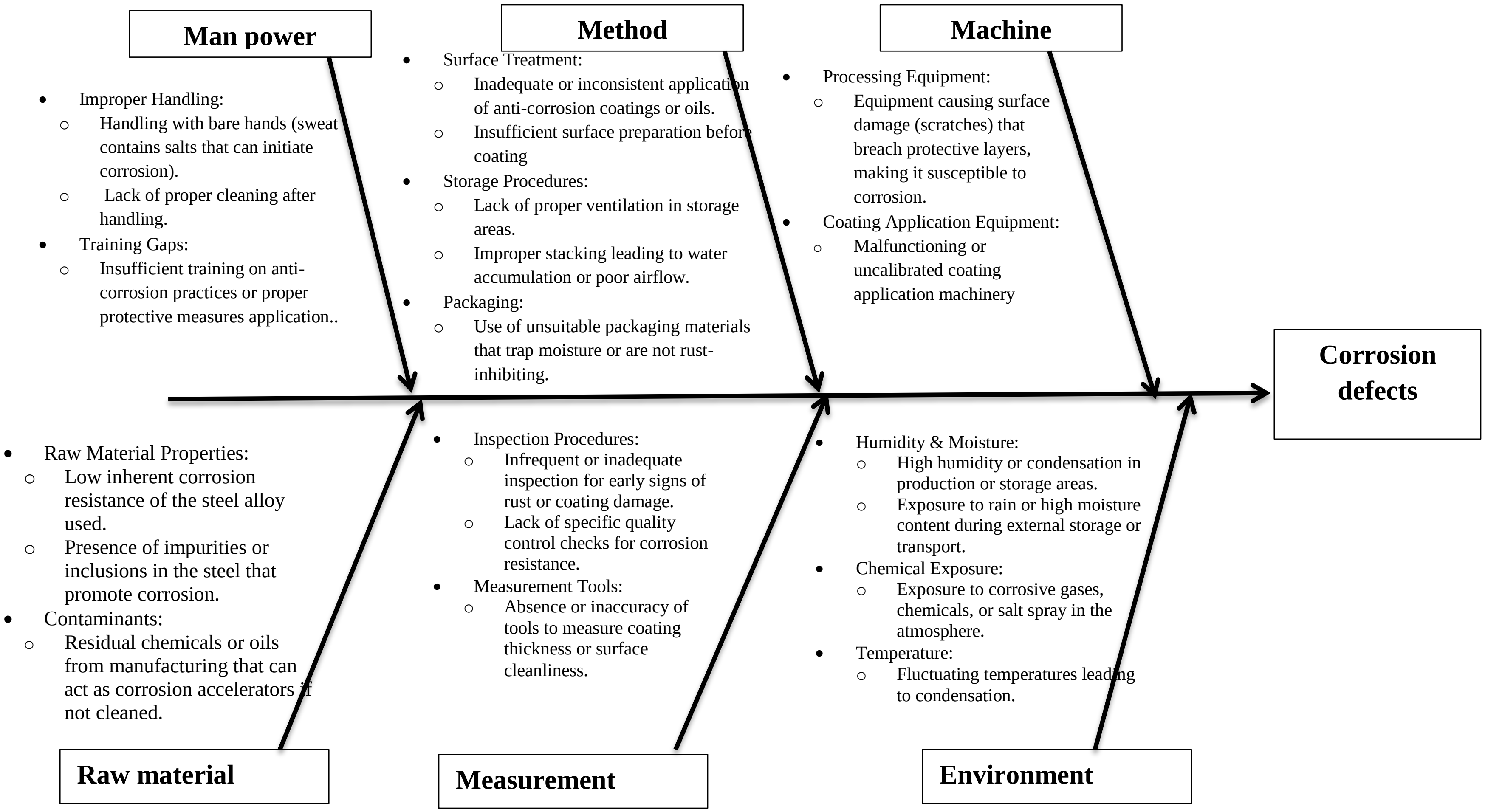


Figure 4.12: Cause and Effect Diagram: Corrosion Defects

A combination of equipment, procedural, and material-related problems led to the identification of three main fault types: corrosion, off-cut-specification dimension, and material (raw material). Inaccurate operational processes and worn or miscalibrated cutting and forming equipment are the primary causes of off-cut-specification dimension problems. Poor supplier quality and insufficient inbound inspection and handling procedures are the root causes of material faults, which let inferior raw materials into production. Inadequate surface treatment and inappropriate storage conditions that expose materials to moisture and promote degradation are the main causes of corrosion problems. Improving defect rates and product quality requires addressing these underlying issues.

From a Lean perspective, several of the root causes identified in this study align with classical waste categories. For example, poor calibration of slitting machines resulted in dimensional inaccuracies, which led to product rework a form of Defect waste. Similarly, material corrosion due to poor storage conditions created unnecessary rework and disposal, also categorized as Defects. Waiting times for inspection and manual adjustments reflect the Waiting waste, while the observed material handling inefficiencies in the uncoiling process indicate unnecessary Motion. Although overproduction and excess inventory were not quantitatively measured, qualitative observations suggest that unplanned production scheduling may lead to Inventory accumulation. These insights allow the Lean aspect of GLSS to be addressed conceptually, reinforcing the importance of waste identification in future process improvement efforts.

In line with Lean principles, the observed operational inefficiencies at Walia Steel Industry were categorized using the TIMWOOD framework, which classifies the seven types of Lean waste. Table 4.5 presents the mapping of key observed problems or the root causes to the relevant Lean waste categories, along with brief explanations of how each issue contributes to waste.

Table 4.5: Mapping of Observed Production Issues to Lean Waste Categories

	Observed Problem	Lean Waste Category	Explanation
1	Material defects and corrosion	Defects	Rework leads to waste of raw materials and energy.
2	Uncalibrated machinery causing off-dimensions	Overprocessing / Defects	Extra processing needed due to poor quality.
3	Waiting for maintenance or inspection	Waiting	Downtime caused by delays in inspection.
4	Unorganized storage of materials	Motion / Inventory	Extra movement by workers and high inventory levels.
5	Slitting/Uncoiling inconsistencies	Overprocessing	Steps repeated or adjusted due to poor setup.

As shown in Table 4.5, multiple Lean waste types are evident in WSI's current operations. The most critical issues identified include defects due to material corrosion and dimensional inconsistencies, overprocessing caused by uncalibrated machines, and excessive waiting times for inspection and maintenance (lack of preventive maintenance). These insights provide a foundation for targeting improvements in the Analyze and Improve phases of the DMAIC cycle.

Key Findings from the Analysis Phase

During the Analyze phase, the root causes of the three prioritized defect types were investigated using Fishbone (cause-and-effect) diagrams and the 5 Whys technique. These defects were not analyzed in isolation but were each associated with specific production lines identified in the earlier Pareto and MFA analyses.

Identified defects and their causes:

Off-Cut Specification Dimensions

- **Primary Process Line**: Cut to Length-1 (Uncoiling and Slitting)
- **Root Causes**:
    - Inaccurate cutting due to worn or misaligned blades
    - Lack of preventive maintenance and SOP enforcement

Material Defects

- **Primary Process Lines**: Line 38-3 (Removing of Burrs) and Line 76(1) (Raw Material Handling)
- **Root Causes**:
    - Poor coil quality from suppliers
    - Absence of formal material acceptance protocols
    - Inconsistent operator handling techniques

Corrosion

- **Primary Process Lines**: Raw Material, Uncoiling/Slitting, and Strip Leveling/Inspection
- **Root Causes**:
    - Inadequate surface treatment
    - Improper storage conditions exposing materials to moisture.

Finding from the seven wastes

- **Defects** are caused by material corrosion and dimensional inaccuracies, leading to rework and material waste.
- **Overprocessing** results from uncalibrated machines and slitting/uncoiling inconsistencies, requiring repeated or unnecessary processing steps.
- **Waiting** occurs during delays in maintenance and inspection, contributing to production downtime.

- **Motion and Inventory** waste stem from unorganized material storage, causing excessive movement and accumulation of stock.

These issues reflect the presence of multiple Lean wastes (as per the TIMWOOD framework), highlighting areas for targeted improvement in the DMAIC approach.

This analysis established a clear connection between root causes, defect types, and the production lines most responsible and the seven lean wastes.

D) Improve phase

Validation

By asking "Why?" frequently, the 5 Whys approach helps identify the underlying source of an issue. For a primary reason from each of three essential defect kinds, below is 5 Whys analysis: The 5 Whys analysis revealed the root causes behind issues related to people, processes, and technology. By systematically questioning each response, teams can uncover deeper insights that lead to more effective solution and prevent recurrences of the problem.

The following 5 Whys analysis was constructed based on validated responses from semi-structured interviews through group discussions with key personnels.

Table 4.6: The 5 Why Analysis of the vital few defects

Type of defect	Why 1	Why 2	Why 3	Why 4	Why 5
Off-cut-specification dimension	Final product dimensions are inconsistent	Sizing rollers are misaligned and poorly calibrated	No standard schedule for calibration or inspection	Preventive maintenance is not routinely implemented	There is no enforced preventive maintenance system or accountability for sizing equipment
Raw material defects	Inconsistencies and cracks found in steel strips before or during forming	No incoming inspection or quality verification is done on raw material	Suppliers are chosen without formal quality criteria	Procurement does not coordinate with quality or production teams	There is no supplier evaluation process or raw material specification standard
Corrosion defects	Finished steel profiles develop rust before delivery	They are stored in humid and unventilated environments	No packaging or coating is applied to protect surfaces	The organization lacks SOPs for protective handling and storage	Employees have not been trained on corrosion control or environmental management

Systemic flaws in the manufacturing and quality assurance processes of Walia Steel Industry are shown by the examination of the top three defect categories: corrosion defects, off-cut specification dimensions, and defects in raw materials. The main cause of off-cut-specification dimension problems is misaligned and inadequately calibrated size rollers. The lack of an enforced preventive maintenance program and a regular calibration schedule is the reason these issues continue. Dimensional errors brought on by this lack of standardization and maintenance result in material waste and rework, two major wastes mentioned in Lean thinking. Addressing these issues through a robust preventive maintenance program and regular calibration could significantly reduce waste and improve overall efficiency. Implementing standardized processes will not only enhance product quality but also contribute to a more sustainable operational process.

The lack of comprehensive inspection processes at the point of entry is the root cause of raw material flaws, including cracks and irregularities. Procurement decisions are made without consulting the production or quality divisions, and suppliers are chosen without a thorough review procedure. This violates the GLSS principles, which place an emphasis on sustainable procurement procedures and quality at the source; it compromises the dependability of inputs and leads to product failures. This ultimately impact customer satisfaction and damages the company's reputation in the market. To address these issues, it is essential to implement a robust inspection protocol and involve all relevant stakeholders in the procurement process to ensure that only high-quality materials are sourced.

When completed goods are exposed to humid, unregulated environments, corrosion flaws develop. This results from a lack of protective coatings, poor packaging, and standard operating procedures for secure storage. Additionally, workers receive insufficient training on environmental management and corrosion avoidance, which results in preventable scrap and environmental damage. Reducing waste, increasing efficiency, and minimizing environmental effect are the three GLSS goals that operations must align with in order to improve product quality. To achieve these goals, it is essential to implement robust training programs for employees, enhance packaging methods, and establish comprehensive procedures for monitoring environmental conditions. By fostering a culture of awareness and responsibility, organizations can significantly mitigate the risks of corrosion and improve overall product integrity.

The results highlight recurring themes, including the absence of standard procedures, lack of preventive practices, and weak cross-functional coordination. Furthermore, each root cause aligns with specific Lean wastes under the TIMWOOD framework such as, poor calibration leading to Overprocessing, and lack of supplier screening contributing to Defects.

Based on the results of the cause-and-effect analysis and the 5 Whys method, the study identified the main root causes of the three defects, as illustrated in the initial pareto chart of the production process. These three defects occur primarily within the vital few critical process types, highlighting the need for targeted improvements. The study were significantly improved material flow, reduce defect rates, and enhance overall product quality.

Improvement on the line 76(1) raw material: Install a quality gate with chemical, dimensional, and visual inspections at the material entry point. For batch traceability of raw materials, use digital tracking (RFID or barcodes). Use segregated and covered storage to stop contamination and corrosion. To safeguard raw materials, keep an eye on the environmental factors and humidity levels in the warehouse.

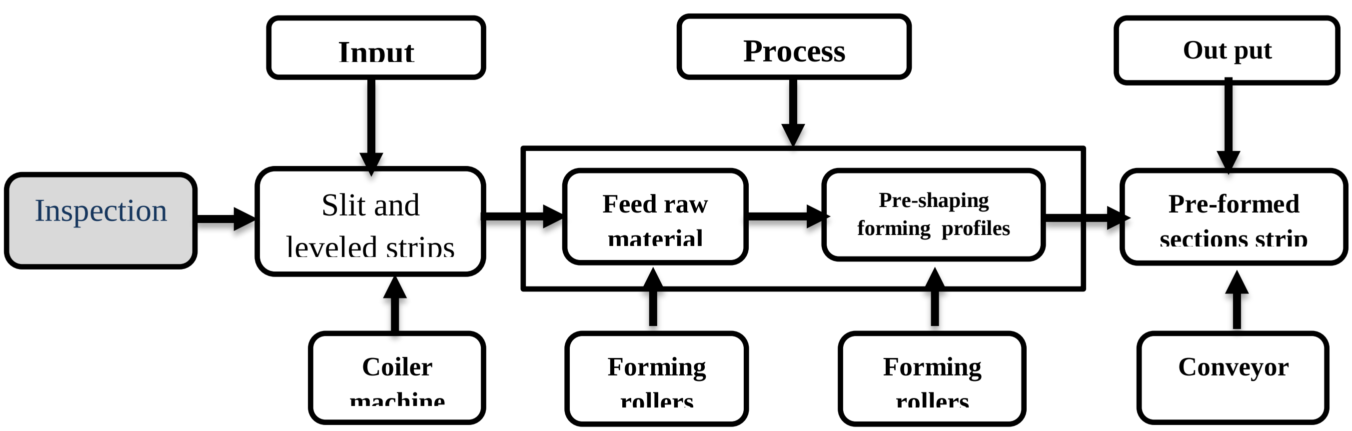


Figure 4.13: Improved process for raw material

Justification of raw material improvement:

- With 22.5 tons of defects traced to incoming materials, poor coil quality and the absence of supplier quality checks were major contributors. Establishing quality gates, strengthening material acceptance criteria, and formalizing supplier feedback systems will help eliminate upstream defects that impact downstream performance.

Improvement on Cut-to-Length-1 slitting and uncoiling: Slitting blades should be calibrated on a regular basis to ensure precise and clean cuts. To improve alignment and lessen stress, install automated tension control devices. To minimize the loss of raw materials, recycle or repurpose cut edges.

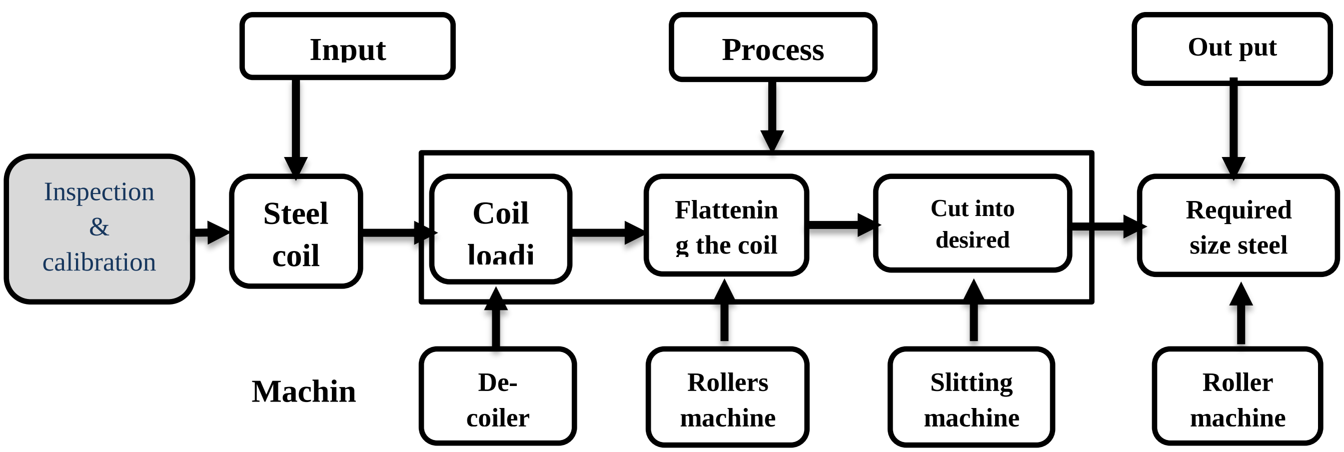


Figure 4.14: Improved slitting and uncoiling process

Justification of Slitting Line (Cut to Length-1):

- This process was the largest single source of off-cut dimension defects, accounting for 39% of total defects. Root cause tools identified blade wear, misalignment, and lack of preventive maintenance as key contributors.

Recalibration, preventive maintenance scheduling, and blade replacement are therefore justified to address this high-impact defect type and reduce unnecessary scrap and CO_2 e emissions.

Improvement on line 76-2 (Strip Leveling and Inspection): Upgrade to hydraulic or servo levelers for improved control over flatness. To find strip flaws, incorporate in-line laser inspection devices. Create a feedback loop based on leveling results for the sourcing of raw materials. Cut down on idle time between forming and leveling to avoid oxidation.

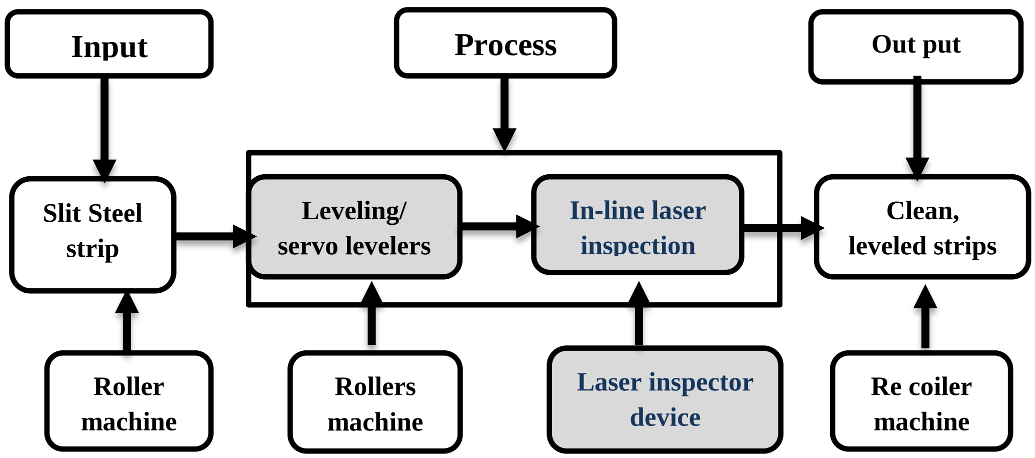


Figure 4.15: Improved Strip Leveling and Inspection

Justification of Strip Leveling and Inspection improvement:

- Responsible for 30 tons of defects, this process introduces quality issues such as warping and surface imperfections. These were linked to improper strip tension and uneven leveling. Upgrading leveling Equipment, improved inspection criteria, and operator retraining are proposed to stabilize this step.

Improvement line 38-3 (Removing of Burrs): Use predetermined removal angles and precise tools to standardize the deburring operation. To find burrs early, install sensors or in-line visual inspection. Gather burr waste for recycling and examination. Train operators how to minimize burr formation by adjusting machine parameters.

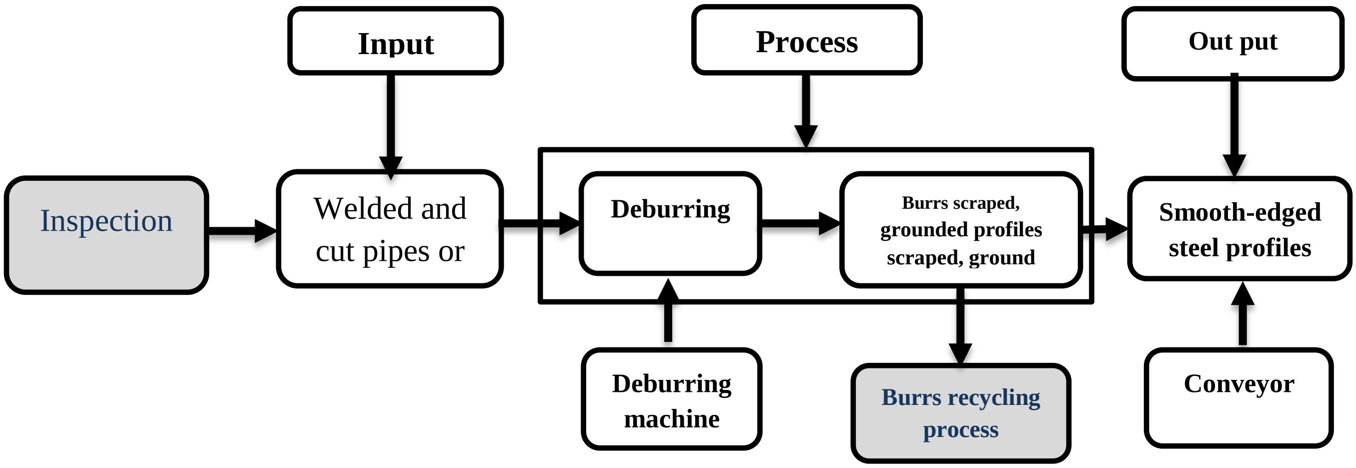


Figure 4.16: Improved removing of burrs process

Justification of Removing of burrs process improvement:

- Contributing 30 tons of defects, this stage causes problems such as over-removal of material and edge damage. These are due to tool wear and lack of precision in deburring. Implementation of tool wear monitoring or inspection, SOP standardization, and applying burr recycling process are justified to prevent material waste.

General improvement

In order to increase overall quality and conform to the tenets of Green Lean Six Sigma (GLSS), a number of focused improvement initiatives are suggested. To guarantee parameter consistency and lower variability, a regular monthly calibration of welding equipment / machine must be carried out. Creating and implementing a **preventive maintenance program** tailored to sizing and forming equipment is crucial for dimensional control. Staff members should receive **training** in the use of sophisticated measuring devices to guarantee dependable output, and tools and rollers should be **calibrated on a regular basis** to preserve dimensional precision.

WSI should implement dust and humidity control systems in storage and packing facilities to solve handling and surface quality issues. Additionally, to reduce scratches and dents during material moving, padded and clearly marked handling practices should be employed. It's also important to create and implement **standard operating procedures (SOPs)** for packaging and protective coatings.

Lastly, the company ought to implement **recycling programs for steel profiles** that are rejected or flawed in accordance with environmental objectives. Additionally stabling recycling the burr plays role for environmental sustainability.

Although the proposed improvements were developed based on quality data and root cause analysis, they also contribute to Lean waste reduction under the TIMWOOD framework. For example, improving material storage reduces both Defect and Inventory waste by preventing corrosion-related scrap. Regular machine calibration reduces Overprocessing and Motion by minimizing the need for manual adjustment. Standardized operating procedures (SOPs) and early inspection checkpoints support the reduction of Waiting and Overprocessing wastes. These links illustrate how Lean principles were inherently embedded in the proposed actions, even if not explicitly framed as such.

E) Control phase

To sustain the improvements achieved through the DMAIC process, a robust control phase is essential. This phase focuses on institutionalizing best practices, monitoring process performance, and ensuring long-term stability in quality and environmental performance. One of the key control measures is the development and enforcement of Standard Operating Procedures (SOPs) for all critical production activities. These SOPs must be documented, easily accessible, and regularly reviewed to ensure compliance with updated process standards and GLSS goals.

Furthermore, tracking defect rates and identifying variances in welding, dimensional accuracy, and surface quality will need the use of statistical process control (SPC) tools, such as control charts. By enabling early intervention when deviations arise, these technologies help to avoid problems from recurring. In order to guarantee that operators are consistently implementing Lean and green principles in their daily tasks, a systematic training and awareness program should also be maintained.

Internal audits should be conducted monthly to assess process adherence, equipment condition, and environmental impact. Feedback loops that enable prompt remedial action and ongoing improvement must be included with these audits. Lastly, the implementation of key performance indicators (KPIs) such as material utilization, rejection rate, and first-pass yield would give management quantifiable results to evaluate the efficacy of the enhancements over time. Walia Steel Industry can guarantee that process enhancements are maintained, quality is upheld, and the advantages of the Green Lean Six Sigma project are completely realized by incorporating these control methods.

The Control phase recommends the ongoing monitoring of quality performance through first-pass yield, defect rate, and Sigma Level, alongside sustainability indicators such as material waste reduction and estimated CO_2 emissions. While the current control strategy emphasizes product quality and environmental sustainability, a more comprehensive GLSS approach also requires attention to operational flow and process efficiency. In addition to the quality and environmental KPIs proposed, future improvement initiatives should also incorporate Lean performance indicators, such as cycle time, material movement frequency, and idle time, to systematically monitor wastes like Motion, Waiting, and Overprocessing. Including these Lean metrics would strengthen the GLSS control framework by maintaining gains in both product quality and process efficiency, and by ensuring that non-value-adding activities remain visible and measurable over time.

Conceptual Identification of Lean Wastes (TIMWOOD)

While this research primarily focuses on quantitative analysis of defect-related waste, which is one of the seven classic Lean wastes, observations and root cause investigations during data collection revealed the presence of other types of waste within Walia Steel Industry’s hollow section manufacturing processes. The seven wastes of Lean, commonly referred to as TIMWOOD (Transportation, Inventory, Motion, Waiting, Overproduction, Overprocessing, and Defects), are frequently used in Lean Thinking to diagnose process inefficiencies.

Due to the limited availability of quantitative data for the other six waste types, this study does not provide numerical analysis for those categories. However, based on production records, operator interviews, and on-site observations, a conceptual mapping of each waste was conducted. This ensures that the Lean dimension of the Green Lean Six Sigma (GLSS) framework is addressed holistically, even in the absence of full data coverage.

Table 4.7 : Conceptual Mapping of Lean Wastes (TIMWOOD) at Walia Steel Industry

	Lean Waste (TIMWOOD)	**Cases in from WSI Case**	**Explanation**
1	T - Transportation	Frequent manual handling of steel strips between processes	No standardized material movement system, increasing time and risk of damage. Seen during slitting/uncoiling and inspection.
2	I - Inventory	Stacked raw materials and semi-finished products left in storage	Poor flow and delay in processing increases work-in-process (WIP); observed during off-spec rework and waiting for inspection.
3	M - Motion	Workers adjusting machines repeatedly due to calibration errors	Extra physical effort caused by lack of standard settings and preventive maintenance. Seen in slitting and forming processes.
4	W - Waiting	Production idle during manual re-inspection or machine recalibration	Downtime between processes and delays in quality checks caused by inconsistencies and poor preparation.
5	O -	Excessive material cut	Although not explicitly measured,

	Overproduction	in anticipation of rework or quality issues	qualitative data suggests that some production is done beyond immediate demand to cover defect losses.
6	O - Overprocessing	Repeated forming and re-inspection of steel profiles	Due to poor quality of raw materials and inconsistent strip leveling, extra effort is required to meet dimensional requirements.
7	D - Defects	Off-spec dimensions, corrosion, cracks in finished profiles	Root causes include poor machine calibration, substandard raw materials, and improper storage—all requiring rework or disposal.

As shown in Table 4.7, various forms of Lean waste exist across WSI's production stages. While Defects are the most prominent and measurable waste—constituting a rejection rate of 3.06% and causing material loss and CO_2 e emissions—the presence of other wastes such as Waiting (e.g., during inspection), Motion (manual adjustments), and Overprocessing (rework due to inconsistent raw materials) were observed qualitatively.

The decision to focus the quantitative analysis of this study on Defects stems from the fact that WSI maintains reliable records for rejection rates and defect types, enabling detailed statistical evaluation (DPMO, Sigma Level). Conversely, waste categories like Transportation or Inventory were not systematically recorded, making it infeasible to conduct a rigorous analysis. Nonetheless, recognizing their presence provides valuable direction for future Lean improvement initiatives within the company.

4.3. Projected Impact of Proposed Improvements

Although the proposed improvements to Walia Steel Industry's steel hollow section production process have not yet been implemented, a scenario-based projection was developed to estimate potential benefits. The projection uses existing defect and scrap data, along with documented outcomes from similar GLSS implementations in developing countries (e.g., Gebreyohannes, 2018; Muchew, 2023; Singh & Sultan, 2019).

Based on a conservative estimate of a 40–50% reduction in defect-related scrap, achievable through blade calibration, SOP enforcement, and improved storage practices consistent with results from GLSS interventions reported in Gebreyohannes, M. G. (2018), Muchew, B. Y. (2023), and Singh, J., & Sultan, I. (2019) the annual defect volume could decrease from 149.83 tons to approximately 80 tons. This would reduce total scrap rate from 2.97% to 1.6%, and CO_2 e emissions from 45 tons to 21 tons annually, assuming a constant 0.3 CO_2 e per ton of waste steel (World Steel Association, 2021).

Figure 4.17: Current vs. Projected Improvements (Annual)

These estimates provide a quantitative rationale for the recommended actions and demonstrate the environmental and operational value of integrating Lean, Six Sigma, and Green tools through the DMAIC framework. The improvement projections are informed by similar GLSS case studies conducted in resource-constrained manufacturing contexts, such as Gebreyohannes, M. G. (2018), who applied Lean Six Sigma and Baldrige frameworks at NAS Foods Plc; Muchew, B. Y. (2023), who used DMAIC to reduce defects in a wood manufacturing firm; and Singh, J., & Sultan, I. (2019), who proposed a GLSS framework in the steel industry.

4.4. Result and Discussion

This part presents the major results of the study and discusses them in alignment with the research questions. Drawing on empirical data from Walia Steel Industry (WSI) and recent literature on Green Lean Six Sigma (GLSS), the findings highlight current practices, process inefficiencies, and opportunities for sustainable improvement in the context of Ethiopian profile steel manufacturing.

The study finds that WSI mostly employs conventional inspection-based quality control techniques in response to the **first research question**, which asks What are the major product defects and quality issues , along with their associated environmental impacts, in Walia Steel Industry's hollow section production process, and how can these be identified and analyzed?

The analysis revealed that WSI's production suffers from several critical quality challenges. Using Pareto charts and annual defect data, the three most significant defect categories were identified as:

- **Off-Cut Specification Dimensions (39%)** — frequently caused by misaligned blades and lack of standard calibration routines.
- **Material Defects (25%)** — stemming from inconsistencies in incoming steel coils and insufficient material verification protocols.
- **Corrosion and Surface Damage (13%)** — arising from improper storage, moisture exposure, and lack of surface protection.

These three categories account for 77% of all defect-related losses. Furthermore, these defect types were found to cluster in four high-risk production stages: Cut to Length-1, Strip Leveling and Inspection, Removing of Burrs, and Raw Material Handling.

The process-wide sigma level of approximately 3.8 (with 1.5σ shift) indicates moderate process capability, emphasizing the need for structured quality improvement.

Research Question 2: How can the GLSS framework through DMAIC be applied to identify root causes, reduce defects, and improve environmental performance in Walia Steel Indudustry?

The GLSS framework applied through the Define, Measure, Analyze, Improve, and Control (DMAIC) phases was effective in evaluating both technical and environmental dimensions of the production system.

- In the **Define** and **Measure** phases, tools such as process mapping, Material Flow Analysis (MFA), and defect categorization established a baseline of performance.
- **Life Cycle Assessment (LCA)**, using cradle-to-gate emission factors (0.3 CO_2 e per ton of steel scrap), was incorporated to quantify the environmental impact of 149.83 tons of annual scrap estimated at 45 tons CO_2 e/year.

The calculated 45 tons of CO_2 e per year resulting from defect-related scrap highlights the indirect environmental impact of quality inefficiencies in WSI's downstream operations. While WSI does not emit carbon through steel production itself, the disposal of defective material effectively wastes all embodied resources associated with upstream activities such as mining, hot rolling, and transportation already embedded in the pre-manufactured steel coils. This means that every ton of scrap represents not only lost product value but also avoidable emissions passed through the supply chain. The potential reduction of 21 tons CO_2 e annually achievable through implementation of GLSS-based improvement measures demonstrates a clear opportunity to align quality enhancement with environmental performance. These findings reinforce the importance of integrating sustainability metrics like carbon intensity alongside traditional quality indicators such as scrap rate and sigma level in continuous improvement efforts. This estimation ensures alignment with WSI’s actual processing scope and avoids overstating environmental impacts.

During the **Analyze** phase, root causes were examined using Fishbone Diagrams and the 5 Whys technique. While these are traditionally team-based tools, the study relied on expert interviews, technical records, and observational data. Each of the three prioritized defects was traced to specific operational lines:

- **Off-Cut Specification**: Rooted in uncalibrated equipment and absent maintenance SOPs, primarily within Cut to Length-1.
- **Material Defects**: Linked to poor procurement coordination and absent material inspection protocols, especially in Raw Material Handling and Burr Removal.
- **Corrosion**: Traced to uncontrolled storage environments and lack of environmental awareness, particularly in Strip Leveling and inspection lines.

While the quantitative analysis of this study focused on defects, the application of Lean principles extended beyond product quality to conceptually address the seven forms of waste (TIMWOOD). Using observations, interviews, and root cause analysis, additional Lean wastes such as **Waiting** (inspection delays), **Motion** (frequent manual machine adjustments), and **Overprocessing** (rework due to poor calibration or surface flaws) were identified in various production stages. Although these were not measured numerically, their presence was mapped in **Table 4.7** and discussed in the context of Lean waste reduction. Recognizing these forms of waste broadens the GLSS analysis, showing that Lean Thinking can still be applied meaningfully even in resource-constrained environments with limited digital tracking. This reinforces the suitability of GLSS for developing countries like Ethiopia, where data limitations often require a mixed-method or conceptual interpretation of Lean waste categories.

The findings highlight systemic weaknesses in preventive maintenance, quality assurance, supplier evaluation, and environmental control all areas where GLSS offers proven solutions.

Based on the GLSS concept and root cause analysis, the study suggested a number of measures to address the **third research question**: What sustainable techniques can be applied to decrease waste and improve operational performance?

The **Improve** and **Control** phases of DMAIC enabled the development of a conceptual improvement framework. Sustainable solutions proposed include:

- Preventive Maintenance for cutting and leveling equipment
- SOP Development and Enforcement for handling, calibration, and inspection
- Material Acceptance Protocols and Supplier Evaluation Tools
- Storage Redesign and Corrosion Prevention Measures
- Environmental and Quality Awareness Training for operators
- Application of MFA and LCA to track material flow and carbon impact

Using projections informed by comparable GLSS implementations, the study estimates that implementing these measures could reduce scrap by up to 46.7%, lowering annual waste from 149.83 to 80 tons and CO_2 e from 45 to 21 tons.

This comprehensive and context-sensitive application of GLSS shows how quality management and environmental sustainability can be addressed simultaneously in a resource-constrained manufacturing environment. The findings support the suitability of DMAIC as a practical operational framework and highlight the value of integrating Lean, Six Sigma, and Green principles to enhance both product quality and environmental performance at WSI to improve product quality while simultaneously addressing environmental impacts. It highlights how Green Lean Six Sigma can transform traditional manufacturing environments by embedding structured problem-solving and sustainability at the core of operations.

A key outcome of this study is the development of a **proposed conceptual framework based on GLSS-DMAIC**, which integrates both quality improvement and sustainability principles. This framework addresses waste reduction and environmental performance in a unified manner. Specifically, the sustainable strategies identified include:

- **Material Flow Analysis** (MFA): Used to map material waste and identify inefficient transitions between process stages.
- **Process redesign**: Focused on improving flow, reducing energy use, and minimizing rework.
- **Preventive maintenance and real-time defect monitoring**: To reduce machine-related variability and prevent environmental burden.
- **Employee training and cross-functional involvement**: Enhancing awareness of quality and sustainability practices.

The study identified the most pressing quality challenges at Walia Steel Industry (WSI) by applying Green Lean Six Sigma (GLSS) tools such as Pareto analysis, Fishbone diagrams, the 5 Whys technique, and the structured DMAIC methodology. These tools enabled a data-driven approach to identifying and understanding the root causes of defects and inefficiencies across critical process lines. The findings not only clarified the key problem areas but also guided the formulation of targeted, practical solutions.

In addition to addressing specific defect categories, the study introduced a conceptual improvement framework that integrates Lean, Six Sigma, and environmental strategies—including Material Flow Analysis (MFA) and Life Cycle Assessment (LCA). This unified approach aims to reduce waste, improve process efficiency, and enhance the sustainability of manufacturing operations.

Overall, the findings demonstrate that the GLSS methodology provides WSI with a structured and adaptable path for improving product quality and minimizing environmental impact. This framework aims to help reduce waste, improve efficiency, and support long-term quality improvement. Overall, the findings suggest that GLSS can offer WSI a clear path toward enhancing both product quality and environmental performance goals that are essential for staying competitive and supporting Ethiopia broader push toward sustainable industrial growth.

While Six Sigma tools such as DPMO, sigma levels, and root cause analysis were central to defect quantification and prioritization, Lean and Green tools were also purposefully embedded throughout the DMAIC process. Lean principles were applied through waste identification (non-value-added processes), process flow mapping, and prioritization of rework and downtime sources. Concurrently, Green (sustainability) dimensions were incorporated using Material Flow Analysis (MFA) to trace material waste and Life Cycle Assessment (LCA) to quantify embodied carbon emissions resulting from defective output. These tools allowed the study not only to identify and reduce defects, but also to minimize waste, improve resource efficiency, and estimate the environmental footprint of WSI's operations. Thus, the integration of Lean, Six Sigma, and Green is evident across the Measure, Analyze, and Improve phases ensuring that both quality and sustainability targets are addressed holistically.

4.5. Proposed conceptual frame work using GLSS

To address the issues identified through the analysis and discussions, this study proposes a conceptual Green Lean Six Sigma (GLSS) framework tailored to Walia Steel Industry. The framework is based on the DMAIC methodology, incorporating Lean tools for waste elimination and Green practices for resource conservation and environmental performance. As illustrated in Figure 4.18, the framework is designed to guide WSI toward defect reduction, sustainable resource use, and continuous process improvement.

As illustrated in the revised framework diagram (Figure 4.17), the model supports WSI's transition toward a proactive, data-driven, and sustainable production system. Each phase of the DMAIC cycle is enriched with appropriate tools:

- **Define**: Identifies CTQ (Critical to Quality) and CTS (Critical to Sustainability) factors, aligns improvement objectives with customer and environmental expectations, and maps processes to locate inefficiencies. Tools: process mapping, stakeholder interviews.
- **Measure**: Focuses on collecting and analyzing quantitative and qualitative data on defects, material flow, and emissions. Tools: Pareto analysis, DPMO, Sigma

Level, Material Flow Analysis (MFA), and Simplified Life Cycle Assessment (LCA).

- **Analyze**: Investigates root causes of high-priority defects and losses. Tools: Fishbone Diagram, 5 Whys, and supporting observational and interview data.
- **Improve**: Proposes corrective and preventive measures such as SOP revision, machine calibration, corrosion prevention, storage redesign, and lean-based strategies like 5S and Kaizen. Sustainable interventions include raw material inspection protocols and eco-friendly handling procedures.
- **Control**: Ensures sustainability through Key Performance Indicators (KPIs) like defect rate, CO_2 emissions, and material utilization rate. Tools include visual controls, audit plans, digital tracking systems, and green procurement standards.

This conceptual framework serves as a strategic roadmap for WSI to move from fragmented quality control toward a fully integrated, data-driven, and sustainability-focused production system. It offers a scalable and practical model that can enhance the company's competitiveness in both local and regional markets, while contributing to Ethiopia’s broader industrial development and environmental goals.

The proposed GLSS framework does not rely solely on Six Sigma tools, but rather achieves synergy by embedding Lean and Green strategies into each DMAIC phase. Each pillar of the framework contributes distinctly: Lean identifies non-value-adding activities (via TIMWOOD), Six Sigma provides tools for defect prioritization and root cause analysis, and Green integrates environmental performance metrics through MFA and LCA.

In the Define and Measure phases, Lean tools such as process mapping and Material Flow Analysis (MFA) were used to highlight bottlenecks and waste hotspots. In addition to flow-based tools, Lean waste identification using the TIMWOOD framework was applied conceptually throughout the Define, Measure, and Analyze phases. Although only Defect waste was quantitatively analyzed, observational data and root cause insights allowed the identification of other non-value-adding activities such as Waiting (e.g., inspection delays), Motion (manual adjustments and unnecessary movements), and

Overprocessing (rework due to poor calibration). This conceptual mapping of Lean wastes summarized in Table 4.7 helped guide solution development in the Improve phase and ensures the framework remains aligned with Lean principles, even in the absence of detailed operational timing data.This helped visualize and prioritize non-value-adding steps and material losses. During the Analyze phase, both Fishbone Diagrams and 5 Whys were enhanced by contextual insights from MFA and Life Cycle Assessment (LCA), enabling the team to trace not only technical root causes but also their environmental implications. The Improve phase introduced Lean-based solutions such as standardized work procedures, preventive maintenance programs, and waste-handling SOPs, while Green strategies focused on recycling burrs, corrosion prevention, and energy-efficient storage and handling. In the Control phase, Lean concepts like visual controls and training reinforcement were paired with Green KPIs including carbon emissions, material utilization rates, and defect-linked waste reduction.

This integrated application of Lean, Green, and Six Sigma methods ensures that process improvements target not only quality and efficiency but also environmental stewardship. The results support the use of GLSS as a practical sustainability-oriented model, particularly in resource-constrained environments like Ethiopian manufacturing. This incorporation of Lean waste categories enhances the practicality of the framework by aligning Lean thinking with real-world inefficiencies observed in WSI's operations, reinforcing the adaptability of GLSS in resource-constrained environments.

As illustrated in the Figure, this framework is not linear but cyclical, promoting feedback loops that allow for adaptive responses to new quality or environmental challenges. The integration of Lean, Six Sigma, and Green dimensions ensures that improvements are holistic, addressing not only efficiency and product quality but also environmental performance and long-term sustainability.

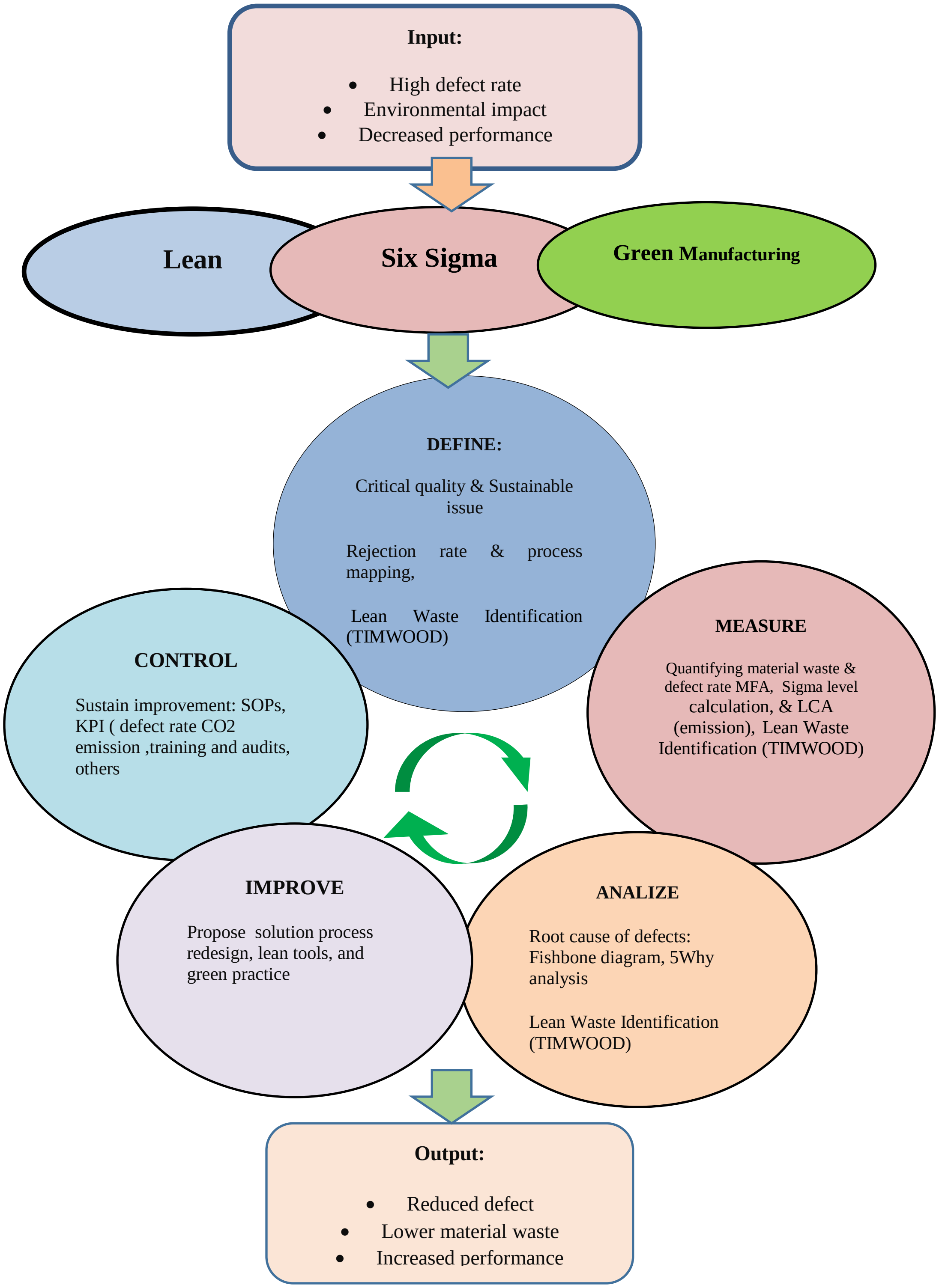


Figure 4.18: Proposed Conceptual Green lean six sigma GLSS framework

The proposed GLSS-DMAIC framework developed in this study is distinguished by its context-specific integration of Lean, Green, and Six Sigma principles into a single, practical improvement structure tailored for resource-constrained manufacturing environments. Unlike existing GLSS models that are often sector-generic or theoretical, this framework is grounded in empirical data from Walia Steel Industry and directly addresses the dual challenges of quality and sustainability.

Its originality lies in several areas:

- It operationalizes the GLSS concept using real-time production and defect data specific to Ethiopia's steel industry.
- It incorporates simplified Life Cycle Assessment (LCA) to quantify carbon emissions associated with material waste.
- It applies Material Flow Analysis (MFA) to identify material inefficiencies and waste hotspots.
- It proposes low-cost and realistic solutions, such as SOP standardization, corrosion prevention strategies, and visual workplace controls methods that are both accessible and implementable in similar developing country settings.

Although full implementation of the framework was beyond the study's scope, validation was achieved through several methods:

- Data triangulation: Cross-referencing defect records, internal documentation, and stakeholder interviews.
- Analytical tools: Root cause tools like Pareto analysis and Fishbone diagrams were used to validate the prioritization of defect types and process lines.
- Projection-based impact estimation: Quantitative estimates of defect reduction (~46.7%) and carbon savings (~21 tons CO_2 /year) were calculated based on literature-supported improvement potential.
- Expert validation: Interviews with supervisors, quality managers, and production operators confirmed the practicality and acceptability of proposed interventions.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Using Walia Steel Industry (WSI) as a case study, this study aimed to investigate the theoretical application of Green Lean Six Sigma (GLSS) as a framework for enhancing quality and sustainability in the steel manufacturing industry. The effectiveness of GLSS approaches in reducing defects, the state of quality control practices currently, and long-term strategies that can improve operational performance was the three primary issues that the study intended to address.

The findings revealed that WSI's existing quality management system is predominantly reactive, relying heavily on traditional inspection-based methods with limited emphasis on preventive and data-driven improvement approaches. By applying the GLSS framework, the study enabled a structured assessment of production inefficiencies and critical defect types. Analytical tools such as Pareto analysis, cause-and-effect diagrams, and the 5 Whys were employed to identify high-impact defects namely off-specification dimensions, inconsistent raw materials, and corrosion along with their root causes, including inadequate machine calibration, poor storage conditions, and insufficient supplier quality control.

Material Flow Analysis (MFA) estimated that approximately 2.97% of total input materials, or 149.83 tons annually, are lost due to product defects. A simplified Life Cycle Assessment (LCA) projected this material loss to result in approximately 45 tons of CO_2 -equivalent (CO_2 e) emissions per year. If the improvement measures proposed in this study such as preventive maintenance, revised standard operating procedures (SOPs), supplier quality enhancements, and optimized storage practices were applied, WSI could potentially reduce defect-related scrap by 46.7%, thereby lowering CO_2 e emissions by an estimated 21 tons annually.

These projections underscore the dual benefits of the GLSS approach: improving operational efficiency while simultaneously advancing environmental sustainability. Unlike conventional quality improvement models, the GLSS framework integrates Lean tools, Green methodologies, and Six Sigma techniques into a cohesive and synergistic system. This integration facilitates comprehensive improvements that address not only defect reduction and cost control but also material efficiency and ecological impact.

Crucially, this study also applied Lean thinking using the TIMWOOD framework to conceptually identify additional wastes such as Waiting, Motion, and Overprocessing. Although only Defects were quantitatively assessed, Lean waste categories were qualitatively mapped across production stages, providing a broader understanding of inefficiencies and strengthening the GLSS integration.

In summary, the study demonstrates that the GLSS framework provides a robust and scalable strategy for steel manufacturers seeking to enhance product quality, reduce waste, and meet sustainability targets. If adopted systematically, it can enable WSI to transition from reactive problem-solving to a culture of continuous improvement, operational excellence, and environmental responsibility thereby strengthening its competitive position in both national and regional markets.

5.2. Recommendation

Based on the research Result and data obtained, the researcher makes the following recommendations:

- Adopt GLSS as a Formal Framework: Green Lean Six Sigma needs to be formally implemented through WSI as an operational strategy for the entire organization. This involves training staff members, forming cross-functional GLSS teams, and utilizing structured techniques for continuous improvement, including DMAIC and Statistical Process Control (SPC).
- Strengthen Preventive Maintenance and Calibration Systems: To minimize technical sources of defects, a preventive maintenance schedule should be utilized

to enforce routine maintenance and calibration of key equipment, particularly slitting, shaping, and sizing machines.

- Improve Raw Material Quality Control: Set in place a strong raw material arriving inspection procedure with clear acceptance standards and a method for evaluating suppliers. To ensure input reliability, cooperation between the production, quality, and procurement divisions is crucial.
- Improve Waste Management and Environmental Practices: Establish official standard operating procedures (SOPs) for packaging, anti-corrosion treatment, and safe storage. To reduce material loss and the impact on the environment, implement recycling and energy auditing procedures as well.
- Use Data-Driven Decision Making: Use technologies such as Material Flow Analysis (MFA) and dashboards for real-time monitoring to keep tabs on material utilization, energy consumption, and errors. Data should be used for strategic planning as well as detecting issues.
- Employee Training and Awareness: Develop targeted training programs on GLSS, quality awareness, sustainability, and equipment handling. Employees at all levels should understand their role in minimizing waste and enhancing quality.

5.3. Future Research Areas

While this study provides a strong foundation, several areas deserve further exploration. Future research should focus on the quantitative analysis of other wastes rather than defect to eliminate in manufacturing industry on implementing the GLSS framework. This will help better enhancements on the overall efficiencies, quality and sustainability

The other further research area recommended is by integrating smart technologies like IoT and real-time monitoring with GLSS could also be studied to enhance quality and sustainability outcomes.

REFERENCE

1. Aichouni, A. B. E., Ramlie, F., & Abdullah, H. (2021). Process improvement methodology selection in manufacturing: A literature review perspective. *International Journal of Advanced and Applied Sciences, 8*(3), 12–20. https://doi.org/10.21833/ijaas.2021.03.002
2. Blaga, P. (2020). The importance of human resources in the continuous improvement of the production quality. *Procedia Manufacturing, 46*, 287–293. https://doi.org/10.1016/j.promfg.2020.03.042
3. Dogan, O., & Gurcan, O. F. (2018). Data perspective of Lean Six Sigma in Industry 4.0 era. *Proceedings of the International Conference on Industrial Engineering and Operations Management* (pp. 943–953).
4. Gholami, H., Jamil, N., Mat Saman, M. Z., Streimikiene, D., Sharif, S., & Zakuan, N. (2021). The application of Green Lean Six Sigma. *Business Strategy and the Environment, 30*(4), 1913–1931. https://doi.org/10.1002/bse.2724
5. Jayaram, A. (2016). Lean six sigma approach for global supply chain management using industry 4.0 and IIoT. *Proceedings of the 2016 2nd International Conference on Contemporary Computing and Informatics (IC3I) (pp.* 89–94). https://doi.org/10.1109/IC3I.2016.7917940
6. Kaswan, M. S., Rathi, R., Garza-Reyes, J. A., & Antony, J. (2023). Green Lean Six Sigma sustainability-oriented project selection and implementation framework for manufacturing industry. *International Journal of Lean Six Sigma, 14*(1). https://doi.org/10.1108/IJLSS-12-2020-0212
7. Laureani, A., & Antony, J. (2012). Critical success factors for the effective implementation of Lean Sigma. *International Journal of Lean Six Sigma, 3*(4), 274–283. https://doi.org/10.1108/20401461211284743
8. Mendonça Júnior, F., Montenegro, M., Thadani, R., Pedroso, G. A. C., & Oliveira, M. A. de. (2018). Industry 4.0 as a way to enhance Lean Manufacturing and Six Sigma. *Fifth European Lean Educator Conference*, November, 152–21.

9. Park, S. H., Dhalgaard-Park, S. M., & Kim, D. C. (2020). New paradigm of lean six sigma in the 4th industrial revolution era. *Quality Innovation Prosperity, 24*(1), 1–16. https://doi.org/10.12776/QIP.V24I1.1430
10. Psarommatis, F., Prouvost, S., May, G., & Kiritsis, D. (2020). Product quality improvement policies in Industry 4.0: Characteristics, enabling factors, barriers, and evolution toward zero defect manufacturing. Frontiers in Computer Science, 2(1-15), Article 26. https://doi.org/10.3389/fcomp.2020.00026
11. Yadav, A., & Sukhwani, V. K. (2016). Quality Improvement by using Six Sigma DMAIC in an Industry. International Journal of Emerging Technologies, 6(6), 41–46.
12. Antony, J. (2021). *Lean Six Sigma for Small and Medium-Sized Enterprises: A Practical Guide*. CRC Press.
13. Oakland, J. S. (2014). *Total Quality Management and Operational Excellence: Text with Cases*. Routledge.
14. Abebe, T., & Bekele, A. (2020). Sustainable manufacturing challenges in Ethiopia. *International Journal of Industrial Engineering, 35*(4), 112–127.
15. Dues, C. M., Tan, K. H., & Lim, M. (2013). Green lean six sigma in manufacturing: A systematic review. *Journal of Cleaner Production, 65*, (pp101–120).
16. Gebremedhin, H., & Mulatu, D. (2022). Energy efficiency and environmental sustainability in Ethiopian industries. *Energy Policy Journal, 78*(2), 56–78.
17. Gholami, R., et al. (2021). The impact of green lean six sigma on sustainable production. *Sustainability Journal, 13*(8), 3456.
18. Kumar, S., et al. (2022). Smart manufacturing and green lean integration. *IEEE Transactions on Industrial Informatics, 18*(5), 1457–1472.
19. Laureani, A., & Antony, J. (2012). Lean Six Sigma: Evolution and future directions. *International Journal of Quality & Reliability Management, 29*(1), 60–82.
20. Zhou, X., et al. (2020). Green lean manufacturing in China: Case studies and insights. *Journal of Manufacturing Processes, 50*, 98–112.

21. Garza-Reyes, J. A. (2015). Lean and Green – A systematic review of the state of the art literature. *Journal of Cleaner Production, 102*, 18–29. https://doi.org/10.1016/j.jclepro.2015.04.064
22. Kaswan, M. S., & Rathi, R. (2020). Investigating the enablers associated with Green Lean Six Sigma for sustainable development: A framework. *Journal of Cleaner Production, 277*, 123–181. https://doi.org/10.1016/j.jclepro.2020.123181
23. Mebratu, D. (2018). Sustainability transitions in Ethiopia's industrial sector: Challenges and opportunities. *African Journal of Sustainable Development, 5*(1), 45–67.
24. Gandhi, J. D., & Thanki, S. (2024). Sustainability index development by integrating Lean Green and Six Sigma tools: A case study of the Indian manufacturing industry. *International Journal of Productivity and Performance Management*.
25. Huang, J., Irfan, M., Fatima, S. S., & Shahid, R. M. (2023). The role of Lean Six Sigma in driving sustainable manufacturing practices: An analysis of the relationship between Lean Six Sigma principles, data-driven decision making, and environmental performance. *Journal of Sustainable Manufacturing, 12*(3), 189–205.
26. Abebe, M., & Tadesse, G. (2024). Challenges in adopting Lean Six Sigma in the Ethiopian manufacturing sector: A case study of the steel industry. *Journal of Manufacturing Sustainability, 14*(2), 95–113.
27. Beyene, A., & Desta, M. (2023). Technological innovation and energy efficiency in Ethiopian manufacturing industries. *Ethiopian Journal of Engineering, 18*(1), 45–61.
28. Hailu, A., & Sisay, G. (2023). Environmental practices and waste management in Ethiopia's industrial sector: Challenges and opportunities. *Environmental Management Review, 22*(4), 122–136.
29. Hassan, M., Yohannes, A., & Fekadu, G. (2023). Implementing green practices in manufacturing: A study of Ethiopia's steel sector. *Journal of Sustainable Industrial Practices, 10*(1), 33–47.

30. Hoffman, L., Zivkovic, M., & Sandoval, R. (2024). Value stream mapping and waste reduction techniques in steel production: A practical approach. *International Journal of Green Manufacturing, 17*(2), 75–92.
31. Liu, J., Yang, L., & Ma, Y. (2024). Reducing material waste in steel production: Global practices and lessons for Ethiopia. *Journal of Industrial Waste Management, 27*(5), 210–224.
32. Mekonnen, T., Ayele, A., & Teshome, S. (2023). Energy efficiency strategies for industrial manufacturing in Ethiopia. *Energy Efficiency Journal, 11*(3), 89–104.
33. Raju, S., & Birehanu, A. (2023). Reducing defects in manufacturing processes using Six Sigma: Evidence from Ethiopia's steel sector. *Quality Improvement Journal, 29*(2), 54–70.
34. Tesfaye, A., & Gebremariam, T. (2023). Strengthening regulatory frameworks for environmental sustainability in Ethiopian manufacturing. *African Journal of Environmental Policy, 20*(3), 134–149.
35. Tadesse, G., & Mekonnen, T. (2022). Quality control in steel manufacturing: Challenges and solutions in Ethiopia. *International Journal of Manufacturing Excellence, 16*(4), 114–128.
36. Tiruneh, S., & Mekonnen, T. (2023). Financial constraints and sustainable manufacturing in Ethiopia's steel sector. *Journal of Finance and Industry, 9*(1), 22–35.
37. Yitbarek, D., & Tefera, H. (2024). Environmental regulation compliance in Ethiopia's manufacturing industry: A review. *Ethiopian Environmental Journal, 25*(1), 78–91.
38. Yohannes, M., Tadesse, S., & Dagnachew, G. (2024). Energy audits and sustainability practices in Ethiopian manufacturing. *Energy Management & Sustainability, 14*(3), 56–71.
39. Ali, A., & Adhikari, A. (2024). Integrated maintenance and quality control strategies for defect reduction in industrial systems. *Journal of Quality in Maintenance Engineering*. https://doi.org/10.1016/j.jmsy.2024.03.005
40. Sadikin, M. A. (2023). Defect reduction in the manufacturing industry: Systematic literature review. *International Journal of Industrial Engineering and*

Engineering Management, *5*(2), 73–83. https://ojs.uajy.ac.id/index.php/IJIEEM/article/view/7495

41. Bengtsson, S., Ohlsson, J., & Larsson, M. (2023). Challenges in integrating sustainability and Lean Six Sigma in the manufacturing industry. *International Journal of Lean Six Sigma*, *14*(2), 155–171. https://doi.org/10.1108/IJLSS-12-2021-0174
42. Wang, Q., Liu, S., & Zhao, L. (2023). GLSS-based energy optimization in China's steel sector: A case study of medium-scale enterprises. *Resources, Conservation & Recycling*, *189*, 106789.
43. Koch, T., Müller, J., & Schneider, F. (2022). Lean, green, and digital: Integrating GLSS with Industry 4.0 in German steel plants. *Procedia Manufacturing, 54*, 890–898.
44. Smith, A., & Rodriguez, J. (2021). Implementing GLSS in U.S. steel manufacturing: Lessons from Nucor and U.S. Steel. J*ournal of Manufacturing Technology Management*, *32*(3), 540–555.
45. Brunner, P. H., & Rechberger, H. (2004). *Practical Handbook of Material Flow Analysis*. CRC Press.
46. Govindan, K., Diabat, A., & Shankar, K. M. (2015). Analyzing the drivers of green manufacturing using a hybrid grey DEMATEL and interpretive structural modeling approach. *Technological Forecasting and Social Change*, *92*, 139–155.
47. Wakjira, M. W., Beshah, B., & Kitaw, D. (2018). Sustainable manufacturing status and research perspective in Ethiopian manufacturing industries. *Procedia Manufacturing, 17*, 780–789.
48. Abebe, K. (2025, February 3). Adoption of sustainable manufacturing practices through IIoT and data analytics in Industry 4.0: A focus on selected Ethiopian manufacturing companies. SSRN. https://ssrn.com/abstract=5122298
49. *Journal of Cleaner Production.* (2022). exploring the relationship between green manufacturing practices and achievement in Ethiopia: A structural equation model. https://link.springer.com/article/10.1007/s41660-022-00261-3

50. Kebede, M., & Worku, B. (2019). Quality management practices in Ethiopian small and medium manufacturing enterprises. *International Journal of Industrial Engineering, 26*(4), 205–218.
51. Ma, J.-L., Chan, T.-M., & Young, B. (2017). Tests on high-strength steel hollow sections: A review. *Proceedings of the Institution of Civil Engineers - Structures and Buildings, 17*0(9), 621–630. https://doi.org/10.1680/jstbu.16.00064
52. Ministry of Industry, Ethiopia. (2021). Industrial Quality Standards and Competitiveness Strategy. Addis Ababa, Ethiopia.
53. Tekle, H., Getachew, D., & Abebe, G. (2020). Challenges in the Ethiopian steel manufacturing industry: Quality and operational perspectives. *Ethiopian Journal of Engineering and Technology, 15*(1), 45-59.
54. Sreedharan, R., & Raju, R. (2024). Green Lean Six Sigma in the food industry: A systematic literature review. *British Food Journal*. https://doi.org/10.1108/BFJ-01-2024-0100
55. Jabbour, C. J. C., Jabbour, A. B. L. d. S., & Godinho Filho, M. (2020). Green Lean Six Sigma and sustainability in SMEs: A systematic review and future research directions. *Business Strategy and the Environment, 29*(8), 3423–3437. https://doi.org/10.1002/bse.2583
56. Mourtzis, D., Angelopoulos, J., & Panopoulos, D. (2022). A GLSS-based model for defect reduction in metal manufacturing: Case study and simulation analysis. *Procedia CIRP*, 107, 153–158. https://doi.org/10.1016/j.procir.2022.05.027
57. Salgado, E. G., Mello, C. H. P., & Silva, A. L. (2021). Quality management maturity and GLSS integration: Evidence from Latin American manufacturing. *Total Quality Management & Business Excellence, 32*(5–6), 591–607. https://doi.org/10.1080/14783363.2019.210304
58. Colias, M. (2024, March 20). American manufacturers seek perfection as quality issues mount. *The Wall Street Journal*. https://www.wsj.com/business/american-manufacturers-seek-perfection-as-quality-issues-mount-6883d6b8
59. Yadav, V., Gahlot, P., Rathi, R., Yadav, G., Kumar, A., & Kaswan, M. S. (2021). Integral measures and framework for Green Lean Six Sigma implementation in

manufacturing environment. *International Journal of Sustainable Engineering, 14*(6), 1319–1331. https://doi.org/10.1080/19397038.2021.1970855

60. Antony, J., Snee, R. D., & Hoerl, R. (2022).*Lean Six Sigma: Yesterday, today and tomorrow.International Journal of Quality & Reliability Management*, **39**(3), 663–680. https://doi.org/10.1108/IJQRM-12-2021-0404
61. Salah, D., Rahim, A., & Carretero, J. (2022).*Integration of Lean and Six Sigma with sustainability: A systematic literature review and agenda for future research. Journal of Cleaner Production*, **350**, 131472.https://doi.org/10.1016/j.jclepro.2022.131472
62. Antony, J., & Snee, R. D. (2020).*Future directions for Lean Six Sigma in manufacturing, service and public sector organizations.International Journal of Quality & Reliability Management*, **37**(1), 153–163.https://doi.org/10.1108/IJQRM-10-2019-0349
63. Setijono, D., & Dahlgaard, J. J. (2021).*Managing quality and innovation for sustainable business performance: A literature review.Total Quality Management & Business Excellence*, **32**(5–6), 499–519.https://doi.org/10.1080/14783363.2019.1640103
64. Jovane, F., Yoshikawa, H., Alting, L., Boer, C. R., Westkämper, E., Williams, D., ... & MacBryde, J. (2008). *The incoming global technological and industrial revolution towards competitive sustainable manufacturing*. *CIRP Annals*, *57*(2), 641–659. https://doi.org/10.1016/j.cirp.2008.09.010
65. Climatiq. (2023). *Emission factor: Metal product manufacturing – downstream processing. Retrieved July 15, 2025*, from https://www.climatiq.io/data/emission-factor/d0c1b1e9-976d-466e-9d55-fd3c27c2882d
66. Steelonthenet.com. (2024). *Steel industry scope 1* CO_2 *emissions – Typical downstream processes. Retrieved July 15, 2025*, from https://www.steelonthenet.com/kb/scope-1-emissions.html

APPENDIXCES

Appendix A: DPMO: Sigma Level Table

	Without 1.5 sigma shift			With 1.5 sigma shift		
Sigma Level	DPMO	Yield	Defect Rate	DPMO	Yield	Defect Rate
1	317310	68.2690000%	31.7310000%	697612	30.23880%	69.76120%
1.1	271332	72.8668000%	27.1332000%	660082	33.99180%	66.00820%
1.2	230139	76.9861000%	23.0139000%	621378	37.86220%	62.13780%
1.3	193601	80.6399000%	19.3601000%	581814	41.81860%	58.18140%
1.4	161513	83.8487000%	16.1513000%	541693	45.83070%	54.16930%
1.5	133614	86.6386000%	13.3614000%	501349	49.86510%	50.13490%
1.6	109598	89.0402000%	10.9598000%	461139	53.88610%	46.11390%
1.7	89130	91.0870000%	8.9130000%	421427	57.85730%	42.14270%
1.8	71860	92.8140000%	7.1860000%	382572	61.74280%	38.25720%
1.9	57432	94.2568000%	5.7432000%	344915	65.50850%	34.49150%
2	45500	95.4500000%	4.5500000%	308770	69.12300%	30.87700%
2.1	35728	96.4272000%	3.5728000%	274412	72.55880%	27.44120%
2.2	27806	97.2194000%	2.7806000%	242071	75.79290%	24.20710%
2.3	21448	97.8552000%	2.1448000%	211927	78.80730%	21.19270%
2.4	16395	98.3605000%	1.6395000%	184108	81.58920%	18.41080%
2.5	12419	98.7581000%	1.2419000%	158686	84.13140%	15.86860%
2.6	9322	99.0678000%	0.9322000%	135686	86.43140%	13.56860%
2.7	6934	99.3066000%	0.6934000%	115083	88.49170%	11.50830%
2.8	5110	99.4890000%	0.5110000%	96809	90.31910%	9.68090%
2.9	3731	99.6269000%	0.3731000%	80762	91.92380%	8.07620%
3	2699	99.7301000%	0.2699000%	66810	93.31900%	6.68100%
3.1	1935	99.8065000%	0.1935000%	54801	94.51990%	5.48010%
3.2	1374	99.8626000%	0.1374000%	44566	95.54340%	4.45660%
3.3	966	99.9034000%	0.0966000%	35931	96.40690%	3.59310%
3.4	673	99.9327000%	0.0673000%	28716	97.12840%	2.87160%
3.5	465	99.9535000%	0.0465000%	22750	97.72500%	2.27500%
3.6	318	99.9682000%	0.0318000%	17864	98.21360%	1.78640%
3.7	215	99.9785000%	0.0215000%	13903	98.60970%	1.39030%
3.8	144	99.9856000%	0.0144000%	10724	98.92760%	1.07240%
3.9	96	99.9904000%	0.0096000%	8197	99.18030%	0.81970%
4	63	99.9937000%	0.0063000%	6209	99.37910%	0.62090%
4.1	41	99.9959000%	0.0041000%	4661	99.53390%	0.46610%
4.2	26	99.9974000%	0.0026000%	3467	99.65330%	0.34670%
4.3	17	99.9983000%	0.0017000%	2555	99.74450%	0.25550%
4.4	10	99.9990000%	0.0010000%	1865	99.81350%	0.18650%
4.5	6	99.9994000%	0.0006000%	1349	99.86510%	0.13490%
4.6	4	99.9996000%	0.0004000%	967	99.90330%	0.09670%
4.7	2	99.9998000%	0.0002000%	687	99.93130%	0.06870%
4.8	1	99.9999000%	0.0001000%	483	99.95170%	0.04830%
4.9	0.96	99.9999040%	0.0000960%	336	99.96640%	0.03360%
5	0.574	99.9999426%	0.0000574%	232	99.97680%	0.02320%
5.1	0.34	99.9999660%	0.0000340%	159	99.98410%	0.01590%
5.2	0.2	99.9999800%	0.0000200%	107	99.98930%	0.01070%
5.3	0.116	99.9999884%	0.0000116%	72	99.99280%	0.00720%
5.4	0.067	99.9999933%	0.0000067%	48	99.99520%	0.00480%
5.5	0.038	99.9999962%	0.0000038%	31	99.99690%	0.00310%
5.6	0.021	99.9999979%	0.0000021%	20	99.99800%	0.00200%
5.7	0.012	99.9999988%	0.0000012%	13.35	99.99867%	0.00134%
5.8	0.007	99.9999993%	0.0000007%	8.55	99.99915%	0.00086%
5.9	0.004	99.9999996%	0.0000004%	5.42	99.99946%	0.00054%
6	0.002	99.9999998%	0.0000002%	3.4	99.99966%	0.00034%

Appendix B: Defects by Production Process

No	Process description	Annual Number of defect in tons	Cumulative Total	Cumulative percentage
1	Raw material	22.5	22.5	15
2	Loading		22.5	15
3	Uncoiling and slitting	37.5	60	40
4	Strip leveling and inspection	30	90	60
5	Loading strip		90	60
6	Roll forming		90	60
7	High frequency welding		90	60
8	Removing of burrs	30	120	80
9	Water cooling		120	80
10	Forming		120	80
11	Product cutting	15	135	90
12	Inspection	15	149.83	100

Source: company data

Appendix C: Defect Type Prioritization

No	Type of defect	Number of defect (in tons/year)	Total percentage	Cumulative
1	Off-cut-specification dimension	47	39%	39%
2	Material	30	25%	64%
3	Corrosion	16	13%	78%
4	Cracking	10.5	9%	87%
5	Scratches	8	7%	93%
6	Porosity	5	4%	97%
7	Incomplete fusion	3	3%	100%

Source: company data

Appendix D: Literature summary

Author(s)	Focus Area	Main Contribution	Tools/Techniques Used or Discussed
Dues, Tan & Lim (2013)	Green Lean concept	Introduced integration of Lean with environmental sustainability.	Green Lean, Lean tools, environmental impact reduction
Laureani & Antony (2012)	Lean Six Sigma in global industries	Explained how LSS improves quality, reduces waste, and influences business culture.	Lean tools, Six Sigma, DMAIC
Yadav & Sukhwani (2016)	Six Sigma in automotive industry	Demonstrated DMAIC's effectiveness in defect reduction and quality improvement.	DMAIC, Pareto chart, cause-effect diagram, SQC
Aichouni et al. (2021)	LSS for performance and cost reduction	Showed how LSS improves efficiency, product quality, and competitiveness.	DMAIC, Lean tools
Gholami et al. (2021)	Green Lean and sustainability	Emphasized alignment of Lean with environmental goals.	5S, JIT, waste reduction, green metrics
Psarommatis et al. (2020)	GLSS framework	Highlighted GLSS's role in reducing waste and improving sustainability.	GLSS, environmental performance indicators
Kaswan et al. (2023)	Integration of Green, Lean & Six Sigma	Provided theoretical foundation for GLSS methodology.	GLSS structure, DMAIC, Lean tools, green metrics
Huang et al. (2023)	Data-driven LSS for environmental gains	Linked LSS with sustainability and analytics in manufacturing.	DMAIC, process analytics, energy audits
Gandhi &	GLSS	Developed tool for	GLSS, Sustainability

Thanki (2024)	Sustainability Index	assessing environmental, social, and economic impact.	Index, Triple Bottom Line
Sreedharan & Raju (2024)	GLSS in food industry	Demonstrated GLSS success using digital tools and employee engagement.	DMAIC, IoT, Industry 4.0 tools, training programs
Jabbour et al. (2020)	GLSS in SMEs	Emphasized leadership and workforce involvement in sustainability adoption.	Lean & Six Sigma, leadership strategies
Salgado et al. (2021)	QMS maturity & GLSS success	Found that GLSS benefits improve with stronger quality infrastructures.	QMS frameworks, Lean & Six Sigma integration
Mourtzis et al. (2022)	GLSS in metal manufacturing	Validated GLSS through real-world improvements in defect and waste reduction.	Simulation, DMAIC, Lean tools
Gebremedhin & Mulatu (2022)	Ethiopian industrial energy inefficiency	Identified energy and regulatory challenges in Ethiopia's industrial sector.	Energy audits, policy review
Beyene & Desta (2023)	Tech barriers in Ethiopian steel sector	Highlighted outdated machinery and low tech adoption in Ethiopian manufacturing.	Tech gap analysis
Tiruneh & Mekonnen (2023)	Financial constraints in Ethiopia	Stressed how lack of funding limits sustainability upgrades.	Cost-benefit analysis, financial feasibility
Abebe & Tadesse (2024)	Workforce skills in Ethiopia	Noted the shortage of skilled professionals for GLSS implementation.	Training needs assessment
Tesfaye & Gebremariam	Policy and regulatory	Reported weak enforcement and lack of sustainability	Policy analysis, institutional capacity

(2023)	support in Ethiopia	incentives.	review
Wang et al. (2023)	GLSS in Chinese steel industry	Showed reduced emissions and improved scrap utilization.	GLSS, waste tracking, emission metrics
Koch et al. (2022)	GLSS and Industry 4.0 in Germany	Demonstrated use of IoT and predictive maintenance in steel production.	IoT, real-time monitoring, SPC, FMEA
Smith & Rodriguez (2021)	GLSS in U.S. steel industry	Highlighted gains in yield, employee engagement, and compliance in large firms.	DMAIC, cross-functional GLSS teams, compliance metrics

Appendix E: Literature gap

Thematic Area	What the Literature Covers	Literature Gap	Key Authors
GLSS Concepts and Integration	Defines and promotes integration of Green, Lean, and Six Sigma for sustainable manufacturing.	Lack of contextualization and adaptation of GLSS in Ethiopian steel profile manufacturing.	Kaswan et al. (2023); Psarommatis et al. (2020)
DMAIC and Quality Improvement	Confirms the effectiveness of DMAIC and other Six Sigma tools for defect reduction.	No application of DMAIC in Ethiopian steel profile industry using real defect data.	Yadav & Sukhwani (2016); Aichouni et al. (2021)
Material Flow Analysis (MFA)	Identifies MFA as effective for resource optimization and waste identification.	Limited integration of MFA within GLSS in Ethiopian manufacturing context.	Brunner & Rechberger (2004); Wakjira et al. (2018)
Financial and Policy Barriers in Ethiopia	Highlights cost, limited incentives, and regulatory gaps affecting sustainability.	No structured GLSS models proposed to overcome these barriers locally.	Tiruneh & Mekonnen (2023); Tesfaye & Gebremariam (2023)
Workforce Skills and Capacity Gaps	Identifies shortage of skilled labor in quality and sustainability practices.	No studies suggest training integration within GLSS for Ethiopian context.	Abebe & Tadesse (2024)

Addis Ababa University

College of Technology and Built Environment

School of Mechanical and Industrial Engineering

Graduate Program in Industrial Engineering

In order to complete my master's degree in industrial engineering, I am conducting research in the Walia steel industry under the title " Application of Green Lean Six Sigma (GLSS) through DMAIC Approach: A Case of Walia Steel Industry (WSI)".

This interview's goal is to pinpoint areas that, in light of the needs of the company product beneficiaries, could use improvement. Your response is crucial to the study's successful conclusion. The information will be kept private and the respondent name will not be revealed during the interview.

Working experience

Current position in the case company

Level of qualification

Gender

The following semi-structured interview questions were designed to support the identification of root causes of key product defects at Walia Steel Industry (WSI), especially in relation to the application of the 5 Whys method. The questions were grouped thematically to guide discussions with production and quality control staff.

Section 1: General Understanding of Quality Practices

1. Can you briefly describe the current quality control procedures in the production process?
2. What are the most common quality issues or product defects you observe during production?
3. How is the quality of incoming raw materials verified?
4. What actions are taken when defects are identified during or after production?
5. Are there preventive maintenance routines or schedules in place for critical equipment?

Section 2: Defect-Specific Exploration (supports 5 Whys)

1. Why do you think the final product dimensions sometimes fall outside of specification?
2. How frequently are the sizing and forming machines calibrated?
3. Is there a standard operating procedure (SOP) for machine setup and calibration?
4. What challenges prevent timely machine maintenance?
5. Who is responsible for monitoring or enforcing calibration schedules?
6. Why are there inconsistencies and cracks in the steel strips?
7. Is there a formal inspection process for raw materials upon arrival?
8. How are raw material suppliers selected or evaluated?
9. Is there any coordination between procurement and quality control departments?
10. Have you encountered issues due to poor material specifications or supplier variability?
11. Why do finished products develop rust before delivery?
12. Are profiles coated or protected in any way after production?
13. Are there guidelines or SOPs for handling or storing steel to prevent corrosion?
14. Have employees received training related to environmental protection or corrosion prevention?
15. What do you think are the main causes of corrosion in finished products?