Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical & Industrial Engineering

Multi-Criteria Decision-Making Methodology for Sustainability Performance Assessment of Plastic Cup Manufacturing: The Case of BA Manufacturing P.L.C.

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University, in partial fulfillment for the Degree of Master of Science in Mechanical Engineering (Manufacturing)

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November 2024

Addis Ababa, Ethiopia

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Declaration Statement

I hereby declare that the work contained in this thesis, "Multi-Criteria Decision-Making Methodology for Sustainability Performance Assessment of Plastic Cup Manufacturing: The Case of BA Manufacturing P.L.C." is entirely original, has not been submitted for a degree from any other university, and has been properly acknowledged in all of the sources of materials used.

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Acknowledgment

First and foremost, I would like to express my deep gratitude to God for granting me the strength and guidance to achieve such a successful outcome. I am sincerely thankful to Dr. Getasew and Mr. Ayalsew, my advisors, for their valuable advice, unwavering support, and the time they dedicated to assisting me throughout the process of this thesis.

I would also like to extend my thanks to the mechanics and employees of BA Manufacturing PLC for their invaluable help in gathering the necessary data.

Lastly, I am grateful to all the staff members at the School of Mechanical and Industrial Engineering, Addis Ababa Institute of Technology, as well as my friends and family, for their continuous encouragement and support throughout the completion of my thesis.

Abstract

Since sustainability is a multidisciplinary concept, it requires strategic prioritization in today's world. Sustainable manufacturing aims to reduce adverse effects while enhancing the supply chain. However, many manufacturers continue to use substantial resources and produce waste and pollution during the process. Therefore, it is essential for manufacturers to seek operations that maximize economic viability and societal well-being while internalizing environmental externalities.

Despite this, there is a lack of an effective multi-criteria decision-making methodology tailored to assess the sustainability performance of plastic cup manufacturing methods, considering the complex interdependencies between environmental, economic, and social dimensions. The purpose of this study is to apply the concept of sustainability to plastic cup manufacturing methods. By using a statistical frequency-counting method for indicator prioritization and carefully selecting indicator sets, the study employs the multi-criteria decision-making (MCDM) methodology of the Analytic Hierarchy Process (AHP) to assess the sustainability performance of these methods.

The assessment examines the sustainability performance of different manufacturing methods and the contributions of various indicators based on the three sustainability pillars. A nine-point Saaty comparison scale is used for pairwise assessments, and the Borda count method is applied for overall sustainability evaluation. According to the analysis, vacuum forming has a higher overall sustainability performance score of 58.23%, compared to pressure forming, which scored 41.74%. The sustainability performance of each method was also examined, along with the contributions of each indicator. In the environmental dimension, pressure forming showed better performance with a score of 5.40%. In contrast, vacuum forming outperformed in the economic and social dimensions, with scores of 9.64% and 21.07%, respectively.

This thesis demonstrates the effective application of a multi-criteria decision-making methodology to evaluate the sustainability performance of cup manufacturing methods. The research also proposes a framework that offers an accurate assessment and comparison of the sustainability performance of injection molding and thermoforming methods, with injection molding performing better.

Keywords: Multi-criteria Decision Making, Sustainability, Sustainable Manufacturing, Analytic Hierarchy Process (AHP), Sustainability Performance Assessment.

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Lists of Abbreviations and Acronyms

AHP	Analytical Hierarchy Process
BAM	BA-Manufacturing PLC
VF	Vacuum forming
PF	Pressure forming
MCDM	Multi-criteria decision making method
OECD	Organization for Economic Cooperation and Development
GP	Goal programming
DEA	Data Envelopment Analysis
MAUT	Multi-Attribute Utility Theory
SWARA	Step -wise Weight Assessment Ratio Analysis
BWM	Best Worst Method
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
CR	Consistency Ratio
CI	Consistency Index
RI	Average Consistency Index
EEP	Ethiopian Electric Power
IM	Injection molding
TF	Thermoforming

List of Symbols

A_{matrix}	Judgment matrix
a_{ij}	Row and Column value of the judgment matrix
$\forall_{i,j}$	All value in row and column
w_{aij}	Weighting value
$A_{normalized}$	Normalized judgment matrix
λ_{max}	The maximum eigenvalue

CHAPTER ONE

1. INTRODUCTION

1.1Background

The report of the United Nations World Commission on Environment and Development provides fundamental operational guidelines and briefly discusses the need for sustainable development [1]. By balancing resource exploitation, investment priorities, technological development, and institutional reform, sustainable development enhances our ability to meet human needs both now and, in the future, [2]. This highlights the strong connection between manufacturing and sustainable development [3], as manufacturing is a primary industry that consumes substantial amounts of energy and raw materials and generates waste. According to the United States Department of Commerce, sustainable manufacturing refers to the creation of products using processes that mitigate negative environmental impacts, preserve natural and energy resources, ensure safety for employees, communities, and customers, and are economically viable [4]. This approach responds to the need for the manufacturing industry to align with sustainable development principles. The decision to adopt this approach was driven by the need for the industrial sector to transition toward sustainability. Since manufacturing affects stakeholders at every stage of a product's lifecycle, the primary focus has been on addressing the material, energy, and waste challenges associated with manufactured products and processes.

Manufacturing sustainability has become an increasingly important topic in both policy discussions and academic research over the past several decades [5], driven by concerns about resource use, energy consumption, and waste generation [6]. As a result, several key methodologies have been introduced, including the triple-bottom line [7], resource efficiency [8], product development [9], human health impact [10], life cycle assessment [11], reverse logistics [12], green consumerism [13], and green and sustainable supply chains [14], among others. These approaches aim to establish manufacturing operations that are ethical, rational, and economically viable. However, one significant gap in this area of study is the integration of sustainability-driven strategies into the competitive orientation of manufacturing organizations.

Such integration is crucial for firms to make informed decisions regarding sustainability-related policies across various industrial decision-making domains.

The adoption of environmentally, economically, and socially responsible processes is a significant challenge not only for the manufacturing sector but also for global activities as a whole [1, 4]. It is evident that, in many parts of the world, there remains a considerable gap in the integration of sustainability-driven strategies into the competitive orientation of enterprises. This integration is crucial for organizations to make informed, sustainability-relevant policy decisions across various areas of manufacturing.

Plastics are synthetic materials made from polymers, each with distinct properties and applications. Common types include polyethylene (PE) for packaging, polypropylene (PP) for durable goods, and polystyrene (PS) for disposable products. Polyvinyl chloride (PVC) is used in construction and medical applications, while polyethylene terephthalate (PET) is commonly found in bottles and textiles. Acrylonitrile butadiene styrene (ABS) is known for its durability in automotive and electronics, and polycarbonate (PC) is valued for its impact resistance in safety gear. Polyamide (nylon) is strong and often used in textiles and mechanical parts, while polyurethane (PU) is versatile in foams and coatings. Polylactic acid (PLA) offers an eco-friendly alternative for packaging, and thermoplastic elastomers (TPE) combine flexibility with durability. Polyoxymethylene (POM) is ideal for precision mechanical parts. These plastics vary in strength, flexibility, and environmental impact, making them suitable for a wide range of industries [78]. Injection molding, blow molding, and thermoforming are the most common methods for producing plastic cups. To improve production capacity and meet local market demand, BA Manufacturing (BAM) Plc in Addis Ababa, Ethiopia, successfully produced two identical products using two different methods, ensuring effective allocation of supplies [15].

Sustainability assessment methods are tools used to evaluate the environmental, social, and economic impacts of products, processes, or organizations. Common methods include Life Cycle Assessment (LCA), which analyzes environmental impacts from production to disposal; Environmental Impact Assessment (EIA), which assesses the potential environmental effects of projects; and the Triple Bottom Line (TBL), which focuses on social, environmental, and economic sustainability. Other methods include sustainability reporting, ecological footprint analysis, Social Life Cycle Assessment (SLCA), circular economy assessment, and ESG (Environmental, Social, and Governance) metrics, all of which evaluate key sustainability factors. These assessments help organizations identify areas for improvement, ensure the adoption of sustainable practices, and align with frameworks like the UN Sustainable Development Goals (SDGs) [5-14].

The environmental, social, and economic sustainability of the plastic cup manufacturing methods were assessed using the Analytical Hierarchy Process (AHP) approach for multi-criteria decision-making (MCDM) analysis. The overall sustainability of the product manufacturing methods was evaluated, which played a critical role in enhancing production efficiency. This not only contributed to reducing market scarcity at the municipal level but also opened up new international markets through exports.

1.2 Statement of the problem

According to the daily machine attendance sheet (attached in the appendix) from BA Manufacturing P.L.C. [15], the company is under increasing pressure to address sustainability challenges, particularly due to growing environmental concerns, cost-effectiveness issues, and the social impacts of its plastic cup manufacturing processes. This challenge is further compounded by the lack of structured decision-making frameworks that integrate these multiple criteria in a balanced way. The absence of a comprehensive approach limits manufacturers' ability to prioritize sustainability actions and make informed decisions that balance long-term environmental, social, and economic goals. Multi-Criteria Decision Making (MCDM) methods, such as the Analytic Hierarchy Process (AHP), offer a structured approach to tackle such complex problems by enabling decision-makers to evaluate multiple conflicting criteria simultaneously. However, the application of AHP in the specific context of plastic cup manufacturing has not been sufficiently explored in existing literature [79]. The current gap lies in the development and application of an effective MCDM methodology tailored to assess sustainability at BA Manufacturing P.L.C. [15], which would account for the complex interdependencies between environmental, economic, and social dimensions. This research aims to address this gap by developing and applying an AHP-based multi-criteria decision-making framework for the sustainability performance assessment of plastic cup manufacturing.

1.3 Objectives

1.3.1 General Objective

The general objective of this study is to develop and analyze a multi-criteria decision-making methodology for assessing the sustainability performance of plastic cup manufacturing.

1.3.2 Specific Objective

The specific objectives of this study are as follows:

- ☞ To identify the key sustainability challenges and opportunities within the plastic cup manufacturing process.
- ☞ To assess the sustainability performance of plastic cup manufacturing based on selected environmental, social, and economic indicators using multi-criteria decision analysis (MCDA).
- ☞ To evaluate the effectiveness of different manufacturing methods (e.g., injection molding, thermoforming) in terms of their sustainability performance.
- ☞ To propose a multi-criteria decision-making (MCDM)-based framework for evaluating sustainable manufacturing practices.
- ☞ To contribute to the development of a more sustainable decision-making framework for the manufacturing sector, specifically in the context of plastic products.

1.4 Research Questions

- What are the key factors that affect the sustainability performance assessment?
- How has the pairwise comparison approach been use to assess the performance of two different manufacturing methods by resolving the problem at various levels in a decision-making setup?
- How to formulate the judgment matrix of contribution of each indicator with respect to the two different manufacturing method separately?

1.5 Assumptions

In order to model the system under investigation, a few oversimplifying assumptions have to make:

i. The entire indicator that chosen treated the two production methods equally, without any prejudice.
ii. There have not been any noticeable variations in the product or no product variation.
iii. During practicing pair wise comparison judgment matrices, the consistency of weight of every indicator in the hierarchy has been teste equally.

1.6 Scope of the study

This study aimed to apply the Analytic Hierarchy Process (AHP) within the context of Multi-Criteria Decision Making (MCDM) methodologies to assess the sustainability performance of plastic cup manufacturing. The research focused specifically on the operations of a plastic cup production company. The scope of the study included the following key aspects:

- Assessment of Sustainability Performance: The environmental, economic, and social dimensions of sustainability within plastic cup manufacturing were examined. Relevant sustainability indicators were identified and assessed to evaluate the overall impact of the manufacturing process.
- Application of AHP for Multi-Criteria Decision Making: The AHP methodology was applied to compare different manufacturing processes and assess their sustainability performance based on multiple criteria. A judgment matrix was constructed, and pairwise comparisons were conducted to prioritize sustainability factors.
- Case Study Focus: Practical insights were provided into how AHP was implemented in a real-world manufacturing context. The case study highlighted the challenges involved in applying MCDM for sustainability assessments.

- Indicators and Data Collection: The most relevant sustainability indicators for plastic cup manufacturing, such as resource consumption, waste generation, cost efficiency, and environmental impact, were identified. Data were collected through observation and measurement within the company.
- Assessment and Decision Support: The AHP methodology was used to evaluate and rank the sustainability performance of two different manufacturing processes. The results provided decision support for improving sustainability practices and prioritizing improvements in operations.
- Limitations: The research was limited to the specific company under study, and the findings may not be directly applicable to other industries or companies without further adaptation. Additionally, the scope was confined to the application of AHP and did not include other MCDM methods or broader lifecycle analysis methodologies.

In summary, this thesis provided a comprehensive assessment of sustainability performance in plastic cup manufacturing, utilizing AHP as a decision-making tool, with a focus on the practical case study of a manufacturing company. The findings offered valuable insights into how sustainability performance could be quantitatively assessed and improved in manufacturing processes.

1.7 Significance of the study

This thesis made several key contributions to the integration of sustainability in manufacturing, particularly in the plastic cup industry. The study used the Analytic Hierarchy Process (AHP) to assess sustainability performance at BA Manufacturing P.L.C., aiming to provide valuable insights for both the company and the broader industry. The key areas of significance include:

- Enhancing Sustainable Manufacturing Practices: A structured approach was provided to evaluate and improve sustainability in plastic cup production, an industry facing growing environmental scrutiny. By assessing multiple sustainability indicators, the study offered practical recommendations for manufacturers to reduce environmental impact, improve social responsibility, and enhance cost-efficiency.

- Innovative Application of AHP for Sustainability Assessment: The thesis introduced the Analytic Hierarchy Process (AHP) as a tool for sustainability assessment in manufacturing—a relatively underexplored application. AHP was used to prioritize different sustainability factors, guiding companies through complex decision-making processes where multiple, sometimes conflicting, goals had to be balanced. This methodological approach enriched the decision-making toolkit for manufacturers seeking to improve their sustainability performance.

- Actionable Insights for the Case Study Company: Tailored recommendations were provided for the plastic cup manufacturing company to enhance their sustainability efforts. By identifying and ranking key sustainability factors, the research enabled the company to make data-driven decisions that could improve operations, reduce waste, and contribute to a more sustainable future.

- Broader Impact on Industry Standards and Policy: The findings of this thesis were not only beneficial for the company in question but also contributed to informing industry-wide sustainability practices. As manufacturers increasingly prioritized sustainability, this research helped in the development of industry standards and influenced policy promoting eco-friendly production methods and waste reduction.

- Advancing Methodological Approaches: This research demonstrated how AHP, a widely recognized decision-making tool, could be adapted to sustainability assessments in the manufacturing sector. By applying AHP to sustainability evaluation, this thesis presented a novel approach that could serve as a model for future research and practical applications in similar industries.

- Supporting a Sustainable Future: The insights from this research helped address the global challenge of plastic waste and promoted the circular economy. By improving sustainability in plastic cup manufacturing, the study contributed to efforts aimed at reducing environmental damage, improving recycling, and encouraging responsible production and consumption.

1.8 Motivation Statement

The manufacturing industry, particularly sectors such as plastic cup production, is under increasing pressure to adopt more sustainable practices due to growing concerns about plastic waste and its environmental impact. However, evaluating sustainability in manufacturing is complex, as it requires balancing multiple, often conflicting criteria—environmental, social, and economic factors.

In the case of BA Manufacturing P.L.C., a company in the plastic cup production sector, there is a clear need for a systematic approach to assess and enhance sustainability performance. Existing methods for evaluating sustainability may not fully address the diverse and interconnected factors that influence overall performance. Consequently, decision-makers face challenges in identifying the most critical areas for improvement and in making data-driven decisions that align with sustainable practices.

This thesis is motivated by the need to provide a comprehensive framework for sustainability assessment that addresses these challenges. The goal is to apply the Analytic Hierarchy Process (AHP), a proven Multi-Criteria Decision-Making (MCDM) methodology, to evaluate sustainability performance. AHP allows decision-makers to prioritize multiple sustainability criteria, enabling them to identify the most important factors for improving environmental, social, and economic performance in their operations.

The motivation behind this research is to offer a structured, objective, and data-driven approach that can guide manufacturers in the plastic cup industry toward more sustainable practices. By applying AHP, the study aims to help companies make informed decisions, reduce waste, improve efficiency, and align with broader sustainability goals. Additionally, it seeks to provide a model that can be adapted for use in other industries facing similar challenges.

Ultimately, this thesis is driven by the need for a practical and effective decision-making tool to assess and enhance sustainability performance in plastic cup manufacturing. As sustainability becomes increasingly critical in today's manufacturing landscape, the challenges of balancing environmental, economic, and social factors require more structured approaches. By applying the Analytic Hierarchy Process (AHP), this study seeks to provide a systematic framework for evaluating sustainability criteria and guiding decision-makers in prioritizing actions that will have the greatest positive impact. In doing so, this research aims to contribute to a more sustainable manufacturing industry, reduce environmental impacts, and promote responsible production practices that can drive lasting change.

1.9 Organization of the Study

This master's thesis focused on a multi-criteria decision-making methodology for assessing the sustainability performance of two different cup-manufacturing methods using the Analytic Hierarchy Process (AHP). The thesis was organized into five distinct chapters, with the structure outlined in Table 1.1 below:

Table 1.1: Organization of the thesis

Chapter One: the first chapter deals about background of the study, the statement of the problem, objective of the study, scope of the study, limitation of the study, significance of the study, motivation statement, research question, assumption and organization of paper.
Chapter Two: the second chapter contains review of related literature to provide the research trend and gap of the main points on this thesis. It presents an encompassing description of the terminological framework and prerequisites for sustainability performance assessment, presents the method that used to choose the indicators, after which it presents the multi-criteria decision-making approach.
Chapter Three: the third chapter presents about the brief description of the material and methods used in the thesis. This includes descriptions of the study area, research methodology, MCDM method, MCDM model, and AHP hierarchy with consistency test.
Chapter Four: the fourth capture presents about result and discussion of the assessment of the two manufacturing method of cup in the economic, environmental and social pillars.
Chapter Five: the last chapter discusses the conclusion, recommendation and future work of the study based on the above assessment result.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

The literature review was based on the title of the work and comprehensively examined related studies on the definition, requirements, and methods of indicator selection for sustainability performance assessment, before discussing decision-making analysis using the most recent and applicable models.

2.2 Definition of Measuring Performance

Measuring performance was defined as the process of determining how effective and efficient previous actions had been [16]. This definition emphasized efficiency and effectiveness but did not explain how or why to quantify anything. A different definition was offered, noting that performance measurements involved analyzing how well organizations had been managed and the value they provided to customers and clients [16, 17]. For those interested in performance measurement, this definition provided clearer guidance regarding the applicability of assessing the value that must be supplied to customers. Based on these essential concepts, researchers developed performance assessment models. The objective of a performance measurement model was to ensure the systematic collection of data regarding the actions, traits, and outcomes of evaluated performances in order to assess the measurement system, improve performance effectiveness, and provide guidance for decisions regarding the development of the measurement system.

2.3 Requirements for Sustainability Performance Assessment

Numerous efforts have been made to develop standards for identifying efficient sustainability assessment methodologies across various application sectors. According to [17], the criteria listed below should be met when assessing the sustainability of a manufacturing method.

The foundation for creating sustainability assessment frameworks should include the following:

- The indicator framework, which incorporates environmental, social, and economic data, addresses all three aspects of sustainability.
- A variety of measurable indicators are included in the framework.
- The framework has a broad focus, covering local, state, and company levels.
- The framework does not overly rely on another framework or set of rules.

The following criteria were provided by [18] for choosing a suitable set of assessments for the manufacturing industry:

i. Cost-Effective: Can the relevant information be easily gathered or accessed from existing sources?
ii. Meaningful: Will the indicators be easy to understand for both internal and external stakeholders?
iii. Comprehensive: Does the set of performance indicators cover all essential elements and goals of the organization?
iv. Controllable: Can the company, team, manager, or employee significantly influence the desired outcomes?
v. Manageable: Is the list of indicators limited to the basic essentials needed to meet the other criteria?
vi. Robust: Do the indicators cover both leading and lagging indicators for inputs, processes, and results?
vii. Timely: Can measurement occur frequently enough to allow for quick, well-informed decision-making?

The following key assessing characteristics were highlighted in [15-18]:

❖ Consider the requirements of the community, the government, and the business world.
❖ Encourage innovation and expansion, with a focus on continuous improvement.
❖ Coordinate efforts at all levels—local, regional, international, and national.
❖ Be fully compatible with existing business systems and contribute to them.
❖ Ensure that management decisions are based on measurable data.

The most effective criteria for selecting indicators depend on identifying the specific areas of concern for a company and its sector [16-18]. At least one of the following elements is necessary to carry out the assessment:

- The reason for the assessment.
- The scope of the tool.
- Resources available for the assessment.
- Time frame for completion.
- Data availability.

The following sustainability performance indicator characteristics are also essential, as noted in [16, 19]:

- Measurable: A sustainability indicator must be statistically measurable, such as one that assesses economic benefit, social well-being, environmental impact, or technological advancement.
- Relevant and Comprehensive: The indicator must provide valuable data on the sustainability of manufacturing processes. It should be appropriate for measuring performance and consider all the key aspects and goals of the organization.
- Understandable and Meaningful: The indicator should be easily understood by the community, especially by non-experts.
- Manageable: The number of indicators should be kept to a minimum necessary to achieve the measurement goal.
- Reliable: The data provided by the indicator should be reliable.
- Cost-Effective Data Access: The indicator should be based on readily available data that can be accessed from existing sources or be conveniently obtainable when needed.

The basic principles and requirements for sustainability assessment were outlined in [20]. Several principles were examined and addressed in this paper. These guidelines were essential because they help practitioners conduct effective sustainability assessments rather than just basic integrated evaluations [21].

- The Essential Consideration Principle: This principle states that the root causes of social, economic, and environmental aspects of the system, as well as their interactions, should be addressed. It involves concerns with governance, the dynamics of current trends and change drivers, interactions between factors, and the risks or unanticipated factors that may influence decisions beyond borders [20].
- The Broad Participation Principle: Sustainability assessments should seek appropriate approaches to increase legitimacy and relevance, engage with assessment users early on, and reflect public opinion while exercising active leadership [20].
- The Continuity and Capacity Principle: This principle suggests that ongoing monitoring should be integrated into the sustainability evaluation. Periodic assessments and change-responsiveness are both required. Investments are necessary to create and maintain the capacity for continuous assessment.
- The Framework and Indicators Principle: It is necessary to use the most recent data to infer trends and construct scenarios. Standardized measuring methods should be employed whenever possible to ensure comparability. These three components should form the foundation of any sustainability assessment. Furthermore, indicator values should be compared to benchmarks and targets, when possible [20, 21].
- The Adequate Scope Principle: An acceptable time horizon should be used to address both the short- and long-term implications of current policies and human activities. The geographic scope should also capture both their local and global effects [21].
- The Transparency Principle: Transparency of data, sources, models, indicators, and outcomes is critical for sustainability assessments. Public access to findings should be ensured. The choices, assumptions, and uncertainties that affect the outcomes of the assessment should be disclosed and explained, along with reporting funding sources and potential conflicts of interest [20].
- The Effective Communication Principle: To ensure effective communication and reach the widest possible audience, sustainability assessment communications should use simple, clear language. Information should be presented fairly and objectively, supported by advanced visual aids and graphics to facilitate understanding [20].

- The Guiding Vision Principle: The goal of sustainability assessments should be guided by the overarching vision of delivering well-being within the carrying capacity of the biosphere and ensuring its sustainability for future generations [20, 21].

2.4 Sustainability Performance Indicators

Recent literature has introduced two comprehensive product and process sustainability indicators [16]. These two holistically designed methodologies for evaluating sustainability performance encompass the triple bottom line and complete life-cycle approaches. As a result, these approaches can serve as the foundation for creating sustainable manufacturing measures at the systems level.

Indicators can be used to generate comprehensive decision support models that are compatible with total life cycle assessments of sustainability. These assessments consider developments at the product, process, and system levels, enabling sustainability evaluation from all perspectives, as discussed by [22]. For products, which aim to deliver the greatest value for the lowest cost throughout their life cycle, enhanced lifecycle models provide more accurate cost forecasting and product optimization. However, there is no standardized approach for evaluating or comparing the achievements of the targeted triple bottom line. This lack of a unified scale hampers consistent performance assessment, preventing a measure of sustainability, remuneration, and encouragement [16, 20].

A thorough understanding and balanced consideration of all performance indicators is crucial for measuring all dimensions of sustainability. As highlighted in many sustainability guidelines cited by various authors [23], most of the current performance indicators focus more on evaluating environmental, economic, and social performance [24-27]. This includes international indicator frameworks for sustainable development [29], world development indicators [30], and OECD sustainable manufacturing indicators [31].

The author examined existing research on sustainability, sustainable manufacturing, and the capacity of manufacturing to create sustainable products [24, 25, 26, 27, 28]. These studies provided insights for selecting appropriate sustainability performance indicators. Both the current research and previous studies have adopted literature-based frameworks for identifying key indicators. These frameworks focus on the product level, emphasizing the most relevant sustainability performance metrics for both manufacturing processes and final products. The aim is to assess the sustainability performance of manufacturing methods at the product level, ensuring that the selected indicators are closely aligned with the objectives of sustainable manufacturing.

2.4.1 Categories of Sustainability Performance Indicators

Sustainability Performance Indicators (SPIs) are essential tools for measuring a company's performance across the three pillars of sustainability [26]: environmental, social, and economic dimensions [26, 27]. In the context of plastic cup manufacturing, these indicators help assess how well a company's production processes align with sustainability goals while minimizing adverse impacts on the environment, society, and economy.

Sustainability Performance Indicators (SPIs) are essential tools for measuring a company's performance across the three pillars of sustainability: environmental, social, and economic dimensions [26, 27]. In the context of plastic cup manufacturing, these indicators help assess how well a company's production processes align with sustainability goals while minimizing adverse impacts on the environment, society, and economy.

I. **Environmental Indicators** focus on measuring the ecological impact of the manufacturing process. Key metrics include: Resource efficiency (e.g., the amount of plastic used per cup, energy consumption, and water usage), Emissions and waste (e.g., greenhouse gas emissions and waste management practices), Pollution and toxicity (e.g., chemical pollutants and the release of microplastics) [25].

II. **Social Indicators** evaluate the company's impact on its workforce and the local community. Key aspects include: Labor conditions and fairness (e.g., worker safety, wages, and adherence to labor standards), Community impact (e.g., the company’s contributions to the local economy, employment, and social programs), Consumer safety and satisfaction (e.g., health and safety of the products and customer satisfaction levels) [25, 26].

III. **Economic Indicators** focus on the financial performance and market competitiveness of the company. These include: Cost efficiency (e.g., cost per unit of production and savings from sustainable practices), Market competitiveness (e.g., how sustainability affects the company's market position and consumer demand), Return on investment (ROI), which measures the financial returns from investments in sustainability efforts [27].

2.4.2 Role of SPIs in Multi-Criteria Decision Making (MCDM)

In the context of Multi-Criteria Decision Making (MCDM), Sustainability Performance Indicators (SPIs) serve as key criteria for evaluating and comparing alternatives for sustainability improvements [28]. The Analytic Hierarchy Process (AHP), a widely used MCDM methodology, enables decision-makers to assign weights to different SPIs, aggregate them into a comprehensive sustainability score, and prioritize actions for improvement. AHP aids in analyzing trade-offs between competing objectives, such as reducing material use versus increasing energy consumption, thereby providing a clearer overall sustainability assessment [16, 25].

For BA Manufacturing P.L.C., it is essential to tailor the selection of SPIs to the specific characteristics of the plastic cup manufacturing process. This may involve focusing on critical environmental impacts, such as plastic waste generation and energy consumption in injection molding. Social and economic factors, including labor practices, consumer demand for eco-friendly products, and local community engagement, should also be considered. The selected SPIs must align with the company's sustainability goals and strategic objectives to ensure they effectively guide decision-making.

A comprehensive set of SPIs can provide valuable insights into sustainability performance, helping the company not only comply with regulatory standards but also enhance its market reputation by promoting more sustainable production processes.

2.5 Indicator Selection Criteria and Adaptation

In recent years, the challenge of creating sustainable products and ensuring sustainable manufacturing processes across the entire product life cycle has become one of the most pressing concerns of modern industry. As global awareness of environmental degradation and resource depletion grows, sustainability has emerged as a core principle guiding production and consumption practices. A central issue in this context is how to effectively address the sustainability of the economy, society, and environment in the manufacturing process. This challenge is not limited to merely reducing environmental impact; it also encompasses economic viability and social responsibility, all of which must be addressed simultaneously for a truly sustainable system [32].

The concept of sustainability is multifaceted and is often operationalized with sustainability indicators. These indicators are designed to measure and assess the environmental, economic, and social performance of products, processes, or entire organizations. To evaluate the sustainability of a product or its manufacturing process, it is critical to establish appropriate indicator selection criteria. These criteria not only define the boundaries of sustainability but also help quantify progress toward achieving sustainability goals. The selection criteria for sustainability indicators are often drawn from a range of tools such as sustainability standards, eco-labels, and other certification frameworks. These tools are instrumental in managing the broad range of sustainability-related requirements that apply across different sectors of production and consumption. However, despite their growing significance, the concept of sustainability indicator selection criteria remains somewhat ambiguous, with various scholars offering differing definitions and interpretations [33].

2.5.1 Definitions and Importance of Sustainability Indicators Selection Criteria

The term ‘sustainability indicators selection criteria’ can be understood as the essential prerequisites that must be met for a product's manufacturing process to be deemed sustainable. These criteria act as benchmarks for assessing a product's alignment with sustainability goals—whether environmental, economic, or social. In simpler terms, sustainability indicators selection criteria form the foundation upon which sustainability status is awarded to a product or process. Meeting these criteria signals that the product has achieved a level of sustainability that aligns with the overarching goals of sustainable development, offering assurance to stakeholders that environmental and social impacts have been adequately managed. However, the lack of a universally agreed-upon definition has led to variations in the criteria applied across industries and research studies [33].

Several scholars have explored the role of sustainability indicators selection criteria in shaping sustainability assessment frameworks. [36] emphasized that these criteria should cover all three pillars of sustainability: economic, social, and environmental. He argued that these criteria serve as vital tools for identifying opportunities and risks tied to a product's sustainability characteristics. The growing importance of these criteria is reflected in their use for both product development and supply chain management. Companies must assess the impact of their production processes across various sustainability domains to align their operations with sustainable practices. In this way, sustainability indicators selection criteria act as tools for managing trade-offs and optimizing performance across economic, social, and environmental dimensions [34-36].

i. Environmental Sustainability and Indicator Selection: In the context of environmental sustainability, selecting appropriate criteria is critical. Environmental sustainability indicators focus on reducing the ecological footprint of manufacturing processes, addressing issues such as waste generation, resource depletion, and emissions. Sustainability standards often include stringent environmental requirements that suppliers must meet to ensure sustainable production practices. According to [35], environmental sustainability standards are a set of demands placed on suppliers to reduce the consumption of natural resources and lower the environmental hazards associated with production. These standards are designed to improve overall supplier effectiveness by encouraging the adoption of greener, more efficient manufacturing techniques. [37] further argued that integrating environmental criteria into the supply chain not only mitigates risks but also drives innovation and efficiency in resource use.
ii. Economic and Social Sustainability Considerations: Economic sustainability is concerned with creating long-term value, ensuring business profitability, and driving innovation that supports sustainable growth. According to [32,34], indicators of economic sustainability must consider factors such as cost efficiency, long-term viability, and the ability to generate value while minimizing resource consumption. These criteria are essential for companies that seek to remain competitive while meeting sustainability goals.

On the other hand, social sustainability involves ensuring fair labor practices, promoting health and safety in the workplace, and supporting community well-being. [35, 37] argue that social indicators should address concerns such as employee rights, diversity, workplace safety, and ethical considerations in product sourcing. These social indicators ensure that manufacturing processes not only contribute to the economy but also improve the quality of life and equity for workers and communities. By integrating social sustainability criteria into the production process, companies can foster a more responsible and inclusive manufacturing environment.

2.5.2 Integrating Sustainability Criteria into Decision-Making: The Role of AHP

Given the complex nature of sustainability, selecting appropriate indicators and criteria requires a systematic decision-making approach. Multi-Criteria Decision-Making (MCDM) techniques, such as the Analytic Hierarchy Process (AHP), are particularly effective for sustainability assessments as they allow companies to evaluate and prioritize various criteria based on their relative importance. AHP enables decision-makers to compare sustainability indicators across economic, social, and environmental dimensions, providing a structured framework to select the most relevant criteria aligned with specific sustainability goals [16, 34-35].

For BA Manufacturing, AHP could be used to identify the most critical sustainability indicators, considering the company's goals, industry-specific challenges, and stakeholder expectations. By applying AHP, the company can prioritize criteria that align with both its strategic objectives and global sustainability standards. This methodology helps develop a comprehensive sustainability strategy that balances competing demands and optimizes performance across all dimensions.

2.6 Decision Making Analysis

Numerous multi-criteria decision-making techniques have been developed and widely used to solve various decision problems through alternative assessments. However, none of these methods fully meet all user expectations, which likely accounts for the variety of aggregation techniques available. Consequently, analysts may need to adjust their methodologies depending on how performance is aggregated. Most of these methods can be categorized into one of three operational strategies outlined by [38]: (1) using a single criterion in the synthesis process, (2) employing a synthesis ranking technique, or (3) utilizing the interactive, sequential, trial-and-error local judgment technique.

The first strategy, using a single criterion in the synthesis process, has the advantage of excluding incomparability between criteria, unlike the other two strategies. In this approach, preferences are presented a priori. A single (value or utility) function is created from these preferences and then optimized. Key approaches that fall under this methodology include AHP

(Analytic Hierarchy Process), GP (Goal Programming), UTA (Utility Theory Approach), DEA (Data Envelopment Analysis), and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [39].

- AHP (Analytic Hierarchy Process) is used to structure complex problems into a multi-level hierarchy, allowing decision-makers to compare elements based on pairwise judgments and derive relative weights.
- GP (Goal Programming) focuses on solving optimization problems where multiple conflicting goals must be satisfied, offering a systematic approach to find a solution that best balances these competing objectives.
- UTA (Utility Theory Approach) is based on the idea of utility, where decision-makers assess the preference of different alternatives based on utility values assigned to various criteria.
- DEA (Data Envelopment Analysis) is a non-parametric method used to evaluate the relative efficiency of decision-making units (e.g., companies or organizations) by comparing their performance across multiple input and output variables.
- TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) ranks alternatives based on their proximity to an ideal solution, aiming to identify the option closest to the best possible performance across all criteria.

Each of these approaches provides a unique way to handle complex decision-making problems by evaluating and comparing alternatives against various performance measures.

Given the similarities between all of these approaches, selecting the most suitable one can be challenging. Fortunately, comparisons between AHP and two recently developed methodologies—the Step-wise Weight Assessment Ratio Analysis (SWARA) and the Best Worst Method (BWM)—help clarify these choices. The BWM enhances the consistency and uniformity of MCDM methods, providing decision-makers with sufficient capabilities to identify the best outcomes, even when different viewpoints are presented. This approach ensures that all decision-makers accept optimal outcomes. Additionally, the SWARA method uses pairwise comparisons to indicate the relative comparisons of items in a hierarchy, similar to AHP. However, AHP requires more pairwise comparisons than SWARA for the same number of indicators [38-40].

One potential challenge with using many indicators is that comparisons can become inconsistent. The SWARA technique addresses this issue, making it more flexible. However, AHP has an advantage in terms of consistency-checking procedures. The AHP approach employs predefined scales (a nine-point scale), while the SWARA approach allows for more flexibility in expressing judgments. This flexibility makes SWARA assessments less rigid than AHP's use of a nine-point scale [40].

2.6.1 Decision Making Models

Multi-criteria decision-making methods were successfully utilized in the sustainable manufacturing to solve the performance problems related to criteria, alternatives, and indicators [41]. In this section, a comprehensive review of the most recent and applicable multi-criteria decision-making based models for sustainable manufacturing was made.

Multi-criteria decision-making (MCDM) methods have been successfully applied in sustainable manufacturing to address performance issues related to criteria, alternatives, and indicators [41]. In this section, a comprehensive review of the most recent and applicable MCDM-based models for sustainable manufacturing is presented.

i. Miscellaneous Model: is a goal programming approach designed as an optimization method to address manufacturing issues with multiple, often conflicting, objectives. For evaluation, both real-world case studies and computational experiments were conducted. Goal programming was adopted for the continuous improvement of processes and was found to be less subjective and straightforward [41, 42]. In one study, goal programming and AHP were used to assess the efficiency and sustainability of Brazilian chemical industries, considering four variables with 21 performance indicators.

ii. Utility-based models: are value measurement models that include methods such as AHP, simple additive weighting, MAUT (Multi-Attribute Utility Theory), the weighted product method, and the weighted sum method. These approaches have been employed to assess difficulties or indicators in the field of sustainable manufacturing. MAUT is a decision-making technique used to evaluate alternatives based on multiple criteria. However, MAUT was found to be less accurate than AHP, although it does have several advantages, such as risk analysis. Despite this, AHP is more commonly used due to its flexibility. AHP has been extensively employed in sustainable manufacturing to assess enablers. It is considered a simple and flexible technique for handling both qualitative and quantitative criteria. AHP has emerged as a superior tool for decision support in supplier assessment, enabler rating, and indicator prioritization. For example, a study identified the indicators of sustainable manufacturing for the cement industry in Indonesia, considering 19 alternatives under social, environmental, and economic criteria. The AHP method was used to prioritize the indicators, with economic criteria receiving the highest weight (0.3985), followed by environmental criteria (0.3059). Among the 19 alternatives, inventory control was identified as the key indicator, with a weight of 0.0917.

iii. Outranking models: include decision-making methods like ELECTRE and PROMETHEE. ELECTRE (Elimination and Choice Expressing Reality) is used to compare and rank alternatives when multiple criteria are involved, while PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations) focuses on ranking alternatives based on preference functions [43, 46]. These models offer a decision problem statement by providing a practical overview of the problem, which makes them popular in decision-making scenarios due to their comprehensive nature. PROMETHEE has been extensively researched and applied in manufacturing industries. The model is grounded in sociology and mathematics and provides a logical framework for decision-making. PROMETHEE focuses on finding the best possible solution to a problem, rather than simply identifying the best decision. Empirical studies have shown that PROMETHEE is commonly applied to assess sustainable manufacturing practices, while ELECTRE has been used for concept selection when there are numerous alternatives. When the differences between criteria values are not carefully studied or when alternatives are insufficient or neutral, ELECTRE is typically employed. PROMETHEE, on the other hand, is used when full or partial orders are needed. In sustainable manufacturing, PROMETHEE has been employed to select sustainable concepts by considering social, environmental, and economic factors [43, 46]. A study on green manufacturing practices in South India found that PROMETHEE provided a useful decision-making tool. Similarly, ELECTRE was chosen to decide on a sustainable design concept based on 16 evaluation variables, including flexibility, environmental impact, maintenance, and profitability. The study found the adoption of sustainable manufacturing practices across various industries.

iv. Combination Model: Some studies have reported the use of a combination of the above models. For instance, one study focused on identifying sustainable risks in the manufacturing sector by combining FDANP (Fuzzy Decision Analysis and Network Process) with the PROMETHEE technique. The hybrid approach, which combines fuzzy decision-making with multi-criteria decision-making, was applied in a case study of three major surgical cotton-manufacturing enterprises in southern India. The final report identified the most significant long-term risks and provided a template for risk managers in the manufacturing industry. By detecting sustainable risks at an early stage, companies can prevent unfavorable incidents and increase production capacity [48].

2.7 Plastic Manufacturing Methods

Plastics are versatile materials used to create both flexible and rigid products, including plastic cups. The production of plastic cups involves various methods, depending on the material, thickness, and design requirements. The three main techniques for manufacturing plastic cups are injection molding, blow molding, and thermoforming. Below is an overview of each method, along with definitions of key terms.

1. **Injection Molding**: a manufacturing process used to produce rigid, thick-walled plastic cups, such as those made from polypropylene (PP) or polystyrene (PS).

Process [71]:

- ✓ Material Preparation: Plastic pellets (usually thermoplastics like PS, PP) are heated to their melting point, turning them into a liquid. Thermoplastics: Plastics that can be heated and reshaped multiple times.
- ✓ Injection: The molten plastic is injected into a steel or aluminum mold shaped like the desired cup. Mold: A hollow container used to shape the liquid plastic into the desired form.
- ✓ Cooling: As the mold cools, the liquid plastic solidifies to form the cup.

- ✓ Ejection: Once cooled, the plastic cup is ejected from the mold.
- ✓ Finishing: Excess material, such as runners or sprues, is trimmed away. Runners and Sprues: Extra plastic parts that form during injection molding, which are removed after the product is formed.

Advantages [71]:

- High accuracy and the ability to create intricate designs.
- Ideal for thicker, more rigid cups.
- Minimal waste and fast production.

Common Uses [71]:

- ➢ Reusable plastic cups.
- ➢ Cups for hot drinks.
- ➢ Custom-designed cups with complex features.

2. **Blow molding**: is a manufacturing technique used to make thin-walled, often disposable plastic cups, typically made from polypropylene (PP) or polyethylene terephthalate (PET).

Process [71, 72]:

- ✓ Extrusion or Injection: Plastic is heated to form a hollow tube (parison). Sometimes, a preform is created through injection before the blowing process. Parison: A hollow tube of plastic that is inflated to form a product.
- ✓ Blowing: The parison is placed into a mold cavity, and air is blown into it, expanding it to fit the mold's shape.
- ✓ Cooling: The plastic solidifies as the mold cools. Solidification: The process of plastic turning into a solid as it cools.
- ✓ Ejection: Once cooled, the molded cup is ejected from the mold.

Types of Blow Molding:

- Extrusion Blow Molding: Used for simpler shapes and larger volumes. Extrusion: A process where material is pushed through a mold to create a long shape, then cut into desired sizes.
- Injection Blow Molding: Used for smaller, more detailed items requiring higher accuracy.

Advantages [71, 72]:

- Ideal for lightweight, inexpensive cups with thin walls.
- High production speed.
- Suitable for producing disposable cups in large quantities.

Common Uses [71, 72:

- Disposable drinking cups.
- Beverage and fast food restaurant cups.

3. **Thermoforming**: is a manufacturing process commonly used to produce disposable cups from thin plastic sheets, typically made of polystyrene (PS) or polypropylene (PP).

   Process [75]:

   - Heating: A thin plastic sheet is heated until it becomes soft and malleable. Malleable: Capable of being shaped or formed.
   - Forming: A mold is placed over the heated sheet, and air pressure or a vacuum is used to form the plastic into the desired shape. Vacuum Forming: A type of thermoforming where a vacuum is applied to draw the plastic sheet into the mold.
   - Cooling: As the plastic cools, it solidifies into the mold's shape.
   - Trimming: Excess plastic around the edge of the cup is trimmed away. Trimming: The process of cutting away extra plastic to leave a clean finished product.

Advantages [75]:

- ✓ Cost-effective for producing simple, thin-walled cups in large quantities.
- ✓ Can be used to create cups in different sizes using the same method.

Common Uses [75]:

- Disposable cups for cold liquids, such as transparent soft drink cups.
- Deli cups and food containers.

The detailed comparisons of these three common plastic cup manufacturing methods are presented in **Table 2.1** below [71-75].

Table 2.1: Comparison of Manufacturing Methods [71-75]

Method	Material Used	Wall Thickness	Production Speed	Cost (per unit)	Common Applications
Injection Molding	Polystyrene, PP, others	Thick, rigid	Medium to Fast	High (due to mold cost)	Reusable cups, hot beverage cups, custom designs
Blow Molding	PET, PP, PS	Thin, flexible	Very Fast	Medium	Disposable cups, fast food cups
Thermoforming	PP, PS, PET, PVC	Thin, flexible	Fast	Low (simple molds)	Disposable cups, food containers

2.8 Related Works

Table 2.2 lists some related works.

Table 2.2: Related Works

No.	Objective	MCDM method and application area	Methodology used	Key findings
1	Identification and assessment of indicators to sustainable manufacturing [47].	Use AHP method for identification and assessment of indicators for manufacturing industry.	Adopted a utility-based MCDM methodology for the sustainable manufacturing practice.	The finding of the study shows that industries more focused on the economic and social indicators rather than environment indicators and most of the indicators have been consider in the various industries but not uniformly distributed.
2	Concept selection for manufacturing industry [47]	PROMETHEE technique was use for concept selection for manufacturing industries by considering criteria i.e., social, natural, and economic.	Adopted an outranking based model using multi-criteria decision-making method PROMETHEE.	Finding of the study stated that the change of materials in manufacturing was the best orientation and it done at the very first stage to achieve sustainability in the manufacturing industries.
3	The green performance evaluation of electromechanical products [42]	Use GRA, and TOPSIS for the performance evaluation designed to facilitate green manufacturing.	Adopted the integrated MCDM methodology approach for the performance evaluation.	The finding of the study reported that the selection of green design alternatives for green manufacturing has been very important to facilitate green manufacturing in the industries.
4	Assessment of efficiency and sustainability [41]	Used the goal programming and AHP technique for the assessment of efficiency and sustainability of the Brazilian chemical industries.	Use a goal programing approach to build miscellanies based type model for the assessment weighting.	Using a multi-objective Mathematical model, though the optimal schedule was obtained, in which goal programming was adopt for the continuous improvement of the process. It has found that goal programming was less subjective with a straightforward procedure.

5	Identify indicators of sustainable manufacturing [45].	AHP method was use to prioritize indicators in the case of Indonesian cement industries under economic, environmental and social scheme.	Adopted a utility based MCDM methodology under the economic social and environmental scheme	19 alternatives in three criteria i.e., social, environmental, and economical found out economic criteria having a maximum weight of 0.3985, which was further follow, by environmental criteria 0.3059, among the 19 alternatives inventory control were the main indicator with a weight of 0.0917.
6	To rank the drivers for green manufacturing [43].	Two stage frameworks were proposed with the fuzzy approach to rank the drivers for green manufacturing.	Adopted two stage frameworks by Fuzzy-AHP approach as a solution methodology and further sensitivity analysis have done for validation purposes.	Finding suggested that green issues in the global industries have gained importance. It has found that environmental issues in the industries play an important role in manufacturing decisions.
7	Sustainability concept selection [44].	Use ELECTRE method for sustainable concept selection.	Adopted ELECTRE method with outranking methodology for the sustainable concept selection purpose.	Key finding supposed to say that many industries have been adopting sustainable concepts in the manufacturing to survive.
8	Identification and assessment of indicators to sustainable manufacturing [47].	Use AHP method for identification and assessment of indicators for manufacturing industry.	Adopted a utility-based MCDM methodology for the sustainable manufacturing practice.	The finding of the study shows that industries more focused on the Economic and social indicators rather than the three considering dimensions.

2.9 Gap in the Research Literature

The study of sustainability performance assessment within the context of manufacturing industries has gained increasing attention in recent years, as organizations strive to align their operations with sustainability goals [49]. However, despite the growing body of literature on sustainability assessment methods, a notable gap remains in integrating multiple criteria into decision-making processes for specific manufacturing sectors, such as plastic cup production. This gap is particularly evident in the application of Multi-Criteria Decision Making (MCDM) methodologies, such as the Analytic Hierarchy Process (AHP), for evaluating sustainability performance in small to medium-sized manufacturing firms (Saaty, 1980).

The Need for Multi-Criteria Decision Making in Plastic Manufacturing: While several studies have explored MCDM techniques for sustainability assessments in various industries ([50]; [51]), there is limited research that specifically focuses on the plastic manufacturing sector. Even fewer studies have applied AHP as a systematic framework for evaluating sustainability performance in plastic manufacturing. This gap is significant, given the environmental concerns related to plastic production, including resource consumption, waste generation, and carbon emissions [52].

Existing Literature on Sustainability Metrics and MCDM: Existing literature primarily focuses on general sustainability metrics, but it often overlooks a detailed framework for evaluating the multiple sustainability dimensions (environmental, economic, and social criteria) simultaneously in specific contexts, like plastic cup production. A closer examination of the literature [53] reveals that while MCDM methods like AHP have been employed in environmental performance assessments (e.g., evaluating green supply chains or renewable energy alternatives), their application in assessing the sustainability performance of plastic cup manufacturing processes remains largely underexplored.

Case-Specific Sustainability Factors: In addition, few studies have incorporated case-specific factors, such as local production practices, market dynamics, and regulatory frameworks, into sustainability assessment models for the plastic manufacturing sector [54]. These factors are crucial for a more accurate and relevant sustainability evaluation in this industry.

Bridging the Gap Between Theory and Practice: Moreover, the integration of AHP in sustainability performance assessments has largely been theoretical, with limited practical applications in industry-specific contexts. This presents an opportunity to bridge the gap between theory and practice, especially for companies like BA Manufacturing P.L.C., which face the challenge of optimizing production efficiency while meeting increasingly stringent sustainability standards.

Objectives of the Study: This thesis aims to fill the gap in the literature by applying the AHP methodology to evaluate sustainability performance in plastic cup manufacturing, with a focus on the specific case of BA Manufacturing P.L.C. The study will contribute to the field by:

1. Demonstrating the practical application of AHP in a real-world manufacturing setting.
2. Expanding the scope of MCDM techniques in sustainability performance assessments within the plastic manufacturing industry.
3. Incorporating environmental, economic, and social criteria tailored to the specific needs and challenges of the plastic cup manufacturing sector.

By addressing this gap, this research would not only enhance the decision-making process in sustainability assessments but also provide valuable insights for both academics and practitioners working towards more sustainable production practices in the manufacturing sector.

2.10 Summary

This chapter provides a comprehensive description of the terminological framework and the prerequisites necessary for sustainability performance assessment. It begins by outlining the method used to select the indicators that will be employed in the assessment process. Following this, the chapter introduces the multi-criteria decision-making (MCDM) approach as a method for evaluating sustainability performance.

Measuring performance can be understood in two ways: first, as an evaluation of how successful and efficient past actions have been, and second, as an assessment of how the management of organizations and the value they provide to their stakeholders are evaluated. In this context, the chapter fully outlines the specifications for the sustainability performance assessment process.

Rather than considering all possible sustainability indicators, a balanced evaluation of performance indicators across all sustainability-related dimensions is conducted. This approach ensures that a well-rounded view of sustainability performance is achieved. Consequently, the decision strategy that incorporates the most recent and applicable models for sustainability assessment is carefully evaluated and briefly discussed.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Description of the Study Area

Plastic cups are commonly used containers made from plastic, typically for holding beverages. While some are designed to be reusable, others are intended for single use and are disposed of or recycled afterward. In Ethiopia, various companies manufacture plastic cups for different applications [15]. As shown in Fig. 3.1 below, one type of plastic cup produced in Ethiopia is most commonly used for holding juice.

Fig 3.1: Plastic Cup [15]

3.1.2 Manufacturing Method

One of the most popular methods for manufacturing cups is thermoforming. This technique is also used for producing a variety of other products, such as food containers, blister packs, and clamshell packaging. There are two main types of thermoforming machines: vacuum forming and pressure forming machines. Vacuum forming machines use negative pressure to suck a softened sheet of plastic onto the mold, while pressure forming machines use positive pressure to push the softened sheet onto the mold. Vacuum forming machines are often preferred for large-scale production runs because they are faster and can handle larger sheets of plastic. On the other hand, pressure forming machines are typically used for small-scale production runs or for more delicate applications, as they provide greater control over the shaping process [57, 58]. To increase production capacity and streamline the supply chain, BA Manufacturing PLC, as shown in Fig. 3.2, manufactures the same plastic cups using both an automatic servo cup-making vacuum forming machine (a) and an automatic tilt cup-making pressure-forming machine (b), both utilizing the same raw material—transparent polypropylene [15].

(a) (b)

Fig 3.2: Plastic Cups

Injection molding is another highly effective manufacturing method for plastic cups. This process involves melting plastic pellets and injecting them into a mold under high pressure. It is ideal for mass-producing high-precision, high-quality parts with a consistent finish, and is well-known for its efficiency and accuracy. While injection molding supports large-volume production with consistent quality, the initial costs for mold design and manufacturing can be significant, making it less suitable for small production runs [71].

3.1.3 Data Collection, Management and Analysis

Data collection was used to gather both primary and secondary data. The primary data was collected through observation and measurements. To further understand the problem and facilitate the interpretation of the collected data, the author also reviewed related literature, including both published and unpublished documents, such as annual reports, as secondary data.

The collected data were analyzed using both quantitative and qualitative methods. Quantitative methods included calculations for percentage, averages, and frequency distribution. In addition, qualitative methods were used to present data in the form of statements or descriptive words rather than numbers. The material type and characteristics of each method were collected qualitatively, while quantitative data included manufacturing time, raw material costs, weight per part, waste, machine costs, energy consumption, and skill requirements (operator and technician training).

The data, whether qualitative or quantitative, along with the characteristics of each method based on the selected parameters, served as the foundation for the sustainability performance assessment. The outcome of the collected data was used as input for this assessment or evaluation. Sustainability issues in cup manufacturing were analyzed by assessing the production methods, with the selected parameters providing input for the economic, environmental, and social aspects of the evaluation, guided by corresponding indicators.

3.2 Methods

3.2.1 Study Design

Numerous authors have focused on sustainability performance assessment within various organizations. The principles, applicability to engineering products, and contributions to the manufacturing industry have highlighted the significance of this topic for further investigation.

Upon exploring the science of sustainability performance assessment, the challenge was to identify a unique contribution or innovation for the current study. After extensive research and visits to various industries, a plastic cup manufacturing company was selected as the most suitable subject for the assessment. Cups manufactured using two different methods at BAM revealed significant environmental, worker, community health, and safety concerns throughout the production process. These issues suggested an unsustainable manufacturing process, making plastic cup manufacturing an ideal application area for the study. This marked the start of the unique contribution to the field—applying sustainability performance assessment to plastic cup manufacturing.

A key aspect of applying sustainability performance assessment to cup manufacturing was the selection of appropriate indicators. Research keywords were used as reference points, and a statistical frequency-counting method was employed to identify the most relevant indicators for the cup manufacturing process.

During the selection, multiple criteria under the three pillars of sustainability were considered, with a focus on cup manufacturing. All selected indicators were organized using the Analytic Hierarchy Process (AHP) and subsequently applied to assess each manufacturing method. Thus, the identification of clear, measurable, and context-specific indicators for cup manufacturing represented another significant contribution of the study. Furthermore, by implementing multi-criteria decision analysis, the sustainability of the cup manufacturing methods was further evaluated.

As illustrated in the chart in Fig. 3.3 below, the overall concept of the study focuses on transforming the plastic manufacturing industry towards sustainability. The research process followed a structured approach: Prior to commencing the study, a conceptual framework, theoretical framework, and supporting theories were developed. The conceptual framework provided a logically consistent justification for the necessity of the research, shaping the study's design and guiding its progression. This section addresses the questions, "Why is this research important?" and "How does it contribute new knowledge?" The theoretical framework briefly outlines the theories that inform and support the study's findings. In the theory section, the relationships between ideas, claims, and concepts are discussed, contributing to a broader understanding of the subject. The conceptual framework was finalized before data collection, and the selected theory was operationalized to create a structured approach that supported the research questions and guided the analytical methods, including idea generation, prediction, and testing.

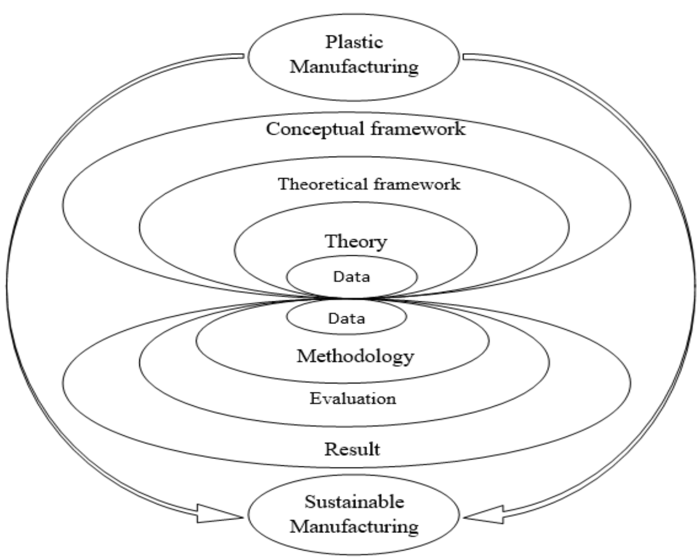


Fig 3.3: Study design

3.2.2 Parameters of the Method

Selecting the appropriate parameters is crucial when assessing sustainability performance. This process helps reduce computational complexity, improves classification efficiency, and prevents the issue of overfitting. Therefore, the key features or parameters of the two manufacturing methods are listed in Table 3.2 to assist decision-makers in making accurate judgments when comparing alternatives based on the corresponding parameter data. The discussion begins with the data related to waste in the two manufacturing methods.

Table 3.1: Recorded data of wastage in one week for VF and PF, respectively

Day	Product per Pc	Waste per kg in VF	Day	Product per Pc	Waste per kg in PF
1	94811	3.15kg	1	17406	2.15kg
2	257022	0.3kg + 0.2kg	2	54020	3.00kg
3	115377	1.85kg + 1.75kg	3	32742	2.10kg
4	43575	0.28kg	4	45774	0.00kg
5	6257	0.00kg	5	3870	0.00kg

As shown in Table 3.1 above, the data of wastage of a single product can be calculated by taking a one week consecutive day recorded data of the two manufacturing method as follows:

$$\mathrm{VF}_{\mathrm{Wastage}} = \sum_{i=1}^{5} \frac{Wastage}{Product} kg = 0.01456g \quad , \quad \mathrm{PF}_{\mathrm{Wastage}} = \sum_{i=1}^{5} \frac{Wastage}{Product} kg = 0.0471g$$

The data of manufacturing time and energy consumption were taken from the machine as shown in Fig 3.4 below.

Fig 3.4 Manufacturing time and energy consumption of the two manufacturing method

Apart from that, the material types used in the manufacturing of the product have been clearly observed in Fig 3.5 below, which belongs to transparent polypropylene.

Fig 3.5: Raw material type

In addition to all the above-recorded data, the overall data taken from the company was verify.

Table 3.2: Features of the two manufacturing methods

Parameters	Vacuum Forming [Automatic servo cup making machine]	Pressure Forming [Automatic tilt cup making machine]
Raw material type	Polypropylene	Polypropylene
Manufacturing time	13560 pc / hr.	11340 pc / hr.
Wastage	0.01456g	0.0471g
Energy consumption	90kw	150kw
Manufacturing cost per part	2.12 Br	2.20 Br
Skill for Operator training Skill for technician training	Six months Eight months	Eight months Ten months
Weight per part	5.00g	5.00g
Raw material cost	67.2 Br/ kg	67.2 Br/ kg

In addition to the parameters mentioned above for each of the two methods, Table 3.3 provides a comprehensive overview of the major characteristics of the vacuum forming (VF) and pressure forming (PF) methods [57, 58]. These characteristics offer more qualitative insights into the production processes of both methods.

Table 3.3: Characteristics of vacuum and pressure forming [57, 58]

Characteristics	Vacuum forming	Pressure forming	Quantitative description
Forming temperature	Higher	Lower	VF 20% higher than PF
Required shaping force	Lower	Higher	PF 2 times more forming force required than VF
Material distribution	Poor	Better	PF 75% better than VF in material distribution
Temperature resistance of the product	Higher	Lower	Directly related to temperature difference and VF 20% higher than PF
Energy consumption	Lower	Higher	PF 1.67 times more energy consumed than VF
Friction between sheet and pre-stretching plug	Higher	Lower	Friction increases with higher material temperature VF = (75-165) °c and PF = (160-200) °c, VF 1.5 times higher than PF.
Manufacturing cost for smaller quantity	Lower	Higher	Given that VF is a little more complicated, the tooling is less expensive, manufacturing takes less time, and the total cost comes to between \$4,000 and \$7,000. & PF ranges from \$2,000 to \$5,000.
Manufacturing cost for large quantity	Higher	Lower	

Table 3.4: Comparisons of injection molding (IM) and thermoforming (TF) manufacturing methods [71-75]

Factor	Injection Molding	Thermoforming
Production cost/ material cost	Has higher material cost (2-6)	Lower material cost (1.5-5)
Actual manufacturing cost/per part cost	0.01-0.05 per cup	0.05-0.15 per cup
Cutting quality	Superior in terms of cutting quality (5 times more)	Lower cutting quality due to the need of trimming.
Surface roughness (Ra)	Low surface roughness (typically Ra <0.8µm)	Higher surface roughness (typically Ra =1.0 -3.0µm)
Production rate	10,000-100,000 cups per hour	3,000 -15,000 cups per hour
Cutting power	Has lower cutting power requirements	Requires more cutting power
Energy consumption	Energy per 1,000 parts: 3–10 kWh	Energy per 1,000 parts: 2–5 kWh
Raw material	The same take it as an assumption	The same take it as an assumption
Material composition	The same take it as an assumption	The same take it as an assumption
Waste management	Lower overall waste due to precision	Higher due to the trimming process
Wastage / weight of release	Material waste: 1-2% (mostly from runners and flash)	Material waste: 5-15% (mostly from trimmings)
Worker health	More exposer workers to a variety of hazards including chemical, heat and noise	Less exposer to molten than injection molding
safety	Has higher safety risks due to complexity of machine	Has fewer mechanical risks
Near misses	Typically has a frequent near misses due to complexity process	Tends to has less near misses
Operator and technician Skills	Skill Level: High (requires setup, monitoring, troubleshooting)	Skill Level: Moderate (requires basic setup, heating, and trimming)

3.2.3 Multi-criteria Decision Making Method

Multi-criteria decision-making (MCDM) involves selecting the best alternative among several potential options based on multiple criteria. MCDM methods are essential tools in manufacturing, helping to address issues characterized by multiple objectives, alternatives, and criteria [59]. In the plastic cup manufacturing process at BAM, several problems related to the environment, worker health, and community safety have been observed. These problems include excessive raw material consumption, resource exploitation, lack of strategic investment, inconsistent manufacturing practices, and the need for technological development. Applying sustainability assessment to the manufacturing methods can address these issues [57, 59].

Various MCDM methods exist, widely used for solving decision problems through the evaluation of alternatives. However, the current investigation focuses on a single function: sustaining the cup manufacturing process. MCDM methods for single-function applications can be categorized into AHP, DEA, FST, TOPSIS, GP, and UTA [60]. Among these, AHP was selected due to its effectiveness, flexibility, simplicity in structuring and solving the problem, and the ability to make assessments using a nine-point scale [61, 63].

The AHP technique was developed after researchers examined how problems are structured and the challenges managers face in solving them. The AHP approach divides the issue into three components. The first component consists of the problem to be solved, the second includes the potential alternatives for the solution, and the third, and most crucial component, involves the criteria used to assess the different solutions [60, 61].

In this research, the problem to be solved is sustainability. The potential alternatives are the main indicators selected under the three pillars of sustainability, and the criteria used to assess different solutions serve as the final indicators for evaluating the various manufacturing method alternatives.

Figure 3.6 below briefly illustrates the multi-criteria structure of this study. Assessing the performance of the two cup manufacturing methods in relation to each of these criteria is equivalent to assessing their sustainability. Therefore, the methodological challenge is to determine the decision-making process that leads to evaluation and conclusions.

Based on this structural hierarchy, a pairwise comparison judgment matrix is utilized at each stage, ensuring consistency verification before using any judgment matrices for result analysis, in line with the study's objectives.

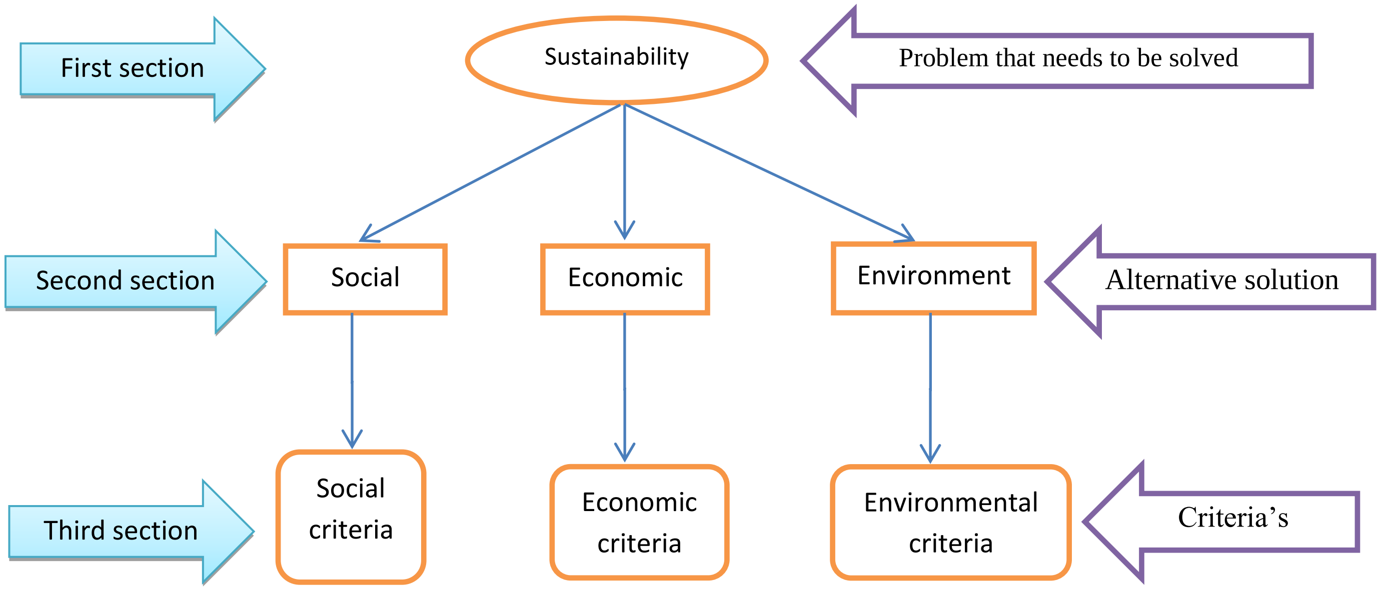


Fig 3.6: MCDM Structure [60, 61]

3.3 Research Methodology

The methodology follows a structured approach, beginning with data collection to address the research gap. Next, indicators are selected based on their statistical frequency, followed by the construction of an AHP hierarchy. The performance of the manufacturing methods is then assessed. A consistency check is performed, and if the results meet the consistency limit, the best method is selected and discussed. If the results do not meet the consistency threshold, the assessment is revised. The overall methodology for conducting the research is summarized in Figure 3.7 below.

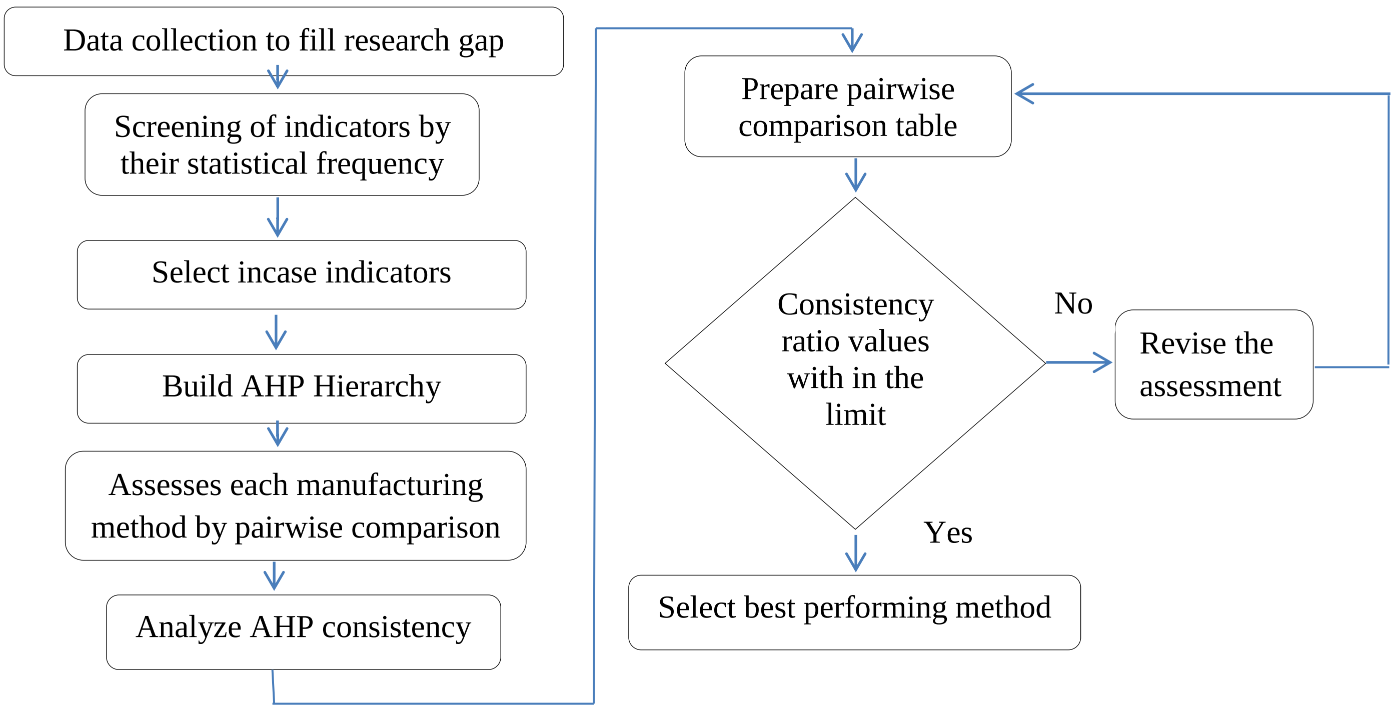


Fig 3.7: Methodology chart

3.4 MCDM Model Building

Model building involved statistical modeling through the development of a probabilistic framework that best describes the relationship between the dependent and independent variables [64]. Multi-criteria decision-making (MCDM) models are inherently complex due to the involvement of economic, environmental, and social factors, which require both managerial and engineering-level analysis [62]. This procedure remains controversial, as the objective of the problem may lead to different solutions at different times, depending on the inputs from the individuals involved in the study [63]. As discussed in the literature section, sustainable manufacturing practices are commonly assessed based on economic, social, and environmental dimensions using various MCDM-based models. The most recent and relevant MCDM models for sustainable manufacturing include utility-based models, outranking models, miscellaneous models [42, 44, 46], and combinations of these models [48]. Each model has its own methods specific to its function, as illustrated in Figure 3.8 below.

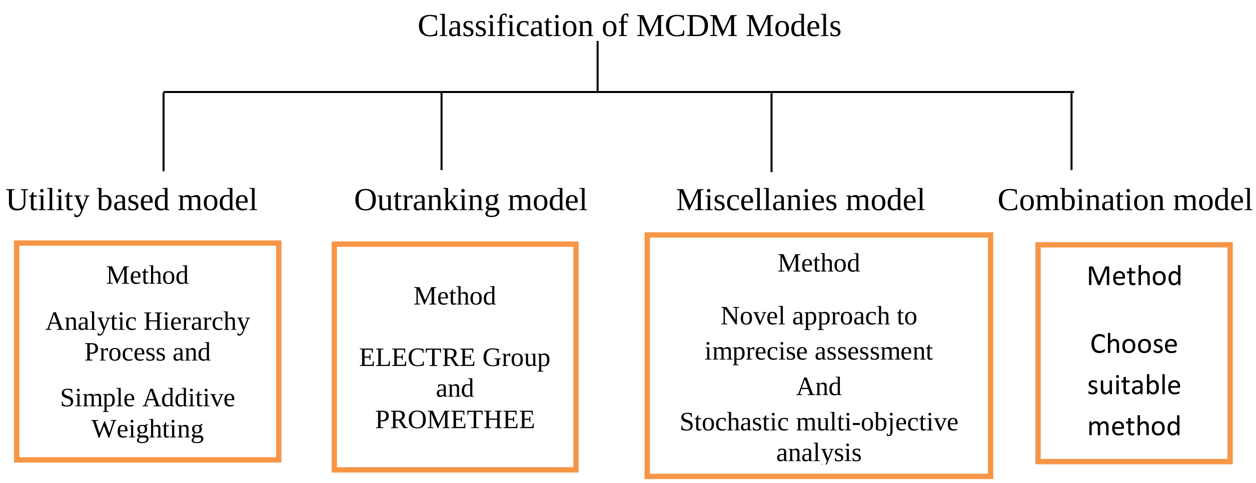


Fig 3.8: Types of models [42,44,46,48]

The outranking model is best suited and more commonly applied in multi-function assessments rather than single-function evaluations [46]. Miscellaneous models, such as goal-programming models, are optimization techniques used to solve manufacturing problems with multiple objectives [42]. These objectives are generally incommensurable and may conflict with each other in the decision-making process.

For the current investigation, the utility-based model is the most appropriate due to its focus on a single functionality and the challenges associated with setting a programming goal because of conflicting objectives in the decision horizon. The input data for the model, through AHP, consisted of indicator weighting assessments under the respective pillars. Although the MCDM model used in the study was based on the AHP hierarchy, it must first pass a consistency test and meet the bonding requirements between dependent and independent variables.

The independent variables for the analysis were the indicators, while the dependent variables included the comparison judgment matrix, AHP hierarchy, and consistency analysis. The interaction of each variable and its contribution to the overall study objective served as the basis for the analysis. For an accurate assessment of the leakages of each indicator, a comprehensive examination of the data and practical implications of various scientific findings was conducted. The following section briefly discusses parts of the model, including indicator selection, the AHP hierarchy, preparation of the judgment matrix, and its consistency.

3.4.1 Indicator selection

Indicators are the backbone of sustainability performance assessment, as they provide crucial information for making informed decisions and can serve as an early warning system to prevent economic, social, and environmental setbacks. Various authors have proposed numerous criteria for selecting indicators. One of the most comprehensive and inclusive criteria for indicator selection is based on sustainability goals, pillars, and objectives [33-37]. As shown in Figure 3.9 below, it briefly demonstrates how the sustainability criteria are distributed across the three pillars.

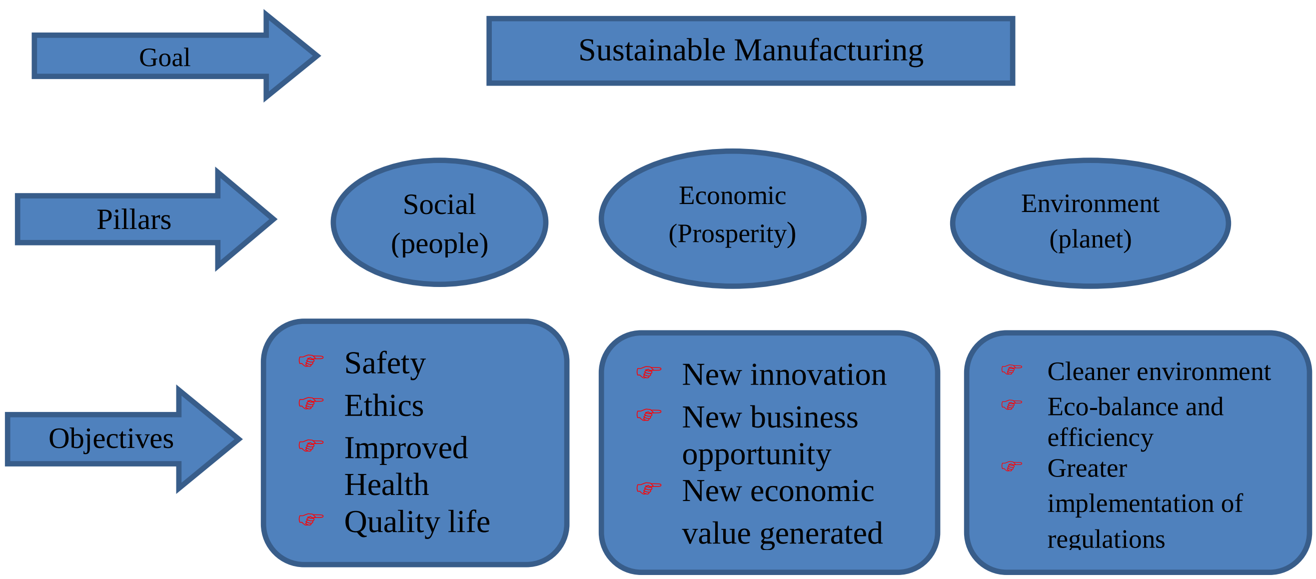


Fig 3.9: Goal, Pillars, and objectives [33-37]

To analyze sustainability performance comprehensively, the sustainability measure considers as much information as possible regarding the set of performance indicators. This approach is based on the primary consideration of the three categories of criteria for indicator selection.

In addition to this framework, secondary considerations include factors such as the manufacturing method, national policies, technology assessment, product type, and the manufacturing environment.

At the third level, various published and unpublished papers, along with different industry reports, were carefully assessed to minimize misconceptions and gather comprehensive information through the selected indicators. This process aimed to facilitate better decision-making and more effective actions by simplifying, clarifying, and aggregating the information.

After applying the aforementioned considerations, a statistical frequency-counting method was employed to evaluate research reports and papers on sustainable manufacturing assessments across the three pillars. Indicators with the highest frequency of usage were then selected.

In addition to using international and global indicator frameworks for sustainable development [29], World Development Indicators [30], and OECD sustainable manufacturing indicators [31], the author also reviewed literature on sustainability, sustainable manufacturing, and the potential of manufacturing to produce more environmentally friendly products while realizing the opportunities for sustainable products [16, 22-28]. This review served as a guideline to propose the following indicators under the three pillars based on their statistical frequency.

3.4.1.1. Economic

The economic dimension is essential for creating sustainable products and assessing the sustainability performance of a manufacturing method, as it encompasses the overall cost across the entire product life cycle. Therefore, the economic pillar must be considered by carefully selecting appropriate indicators within its framework [65]. Once the decision was made to assess the economic performance of plastic cups using indicators, a selective review of economic indicators was conducted [16, 22-31]. These indicators were then organized under the corresponding categories, as shown in Table 3.5:

Table 3.5: Lists of indicators under economic dimension

Manufacturing Cost: Unit Production Cost, Actual Machining Cost, Cost of by-product treatment, Governmental Policies, Machine Tool Usage Cost, Administrative Burdon, Public authority, Property right, Cutting and Lubrication Fluid Cost.	Machining Performance: Surface Roughness, Cutting Quality, Cutting Temperature, Machining induced variations.	Production Efficiency: Production rate, Cutting Power, Material Removal Rate.	Process Improvement: Process Management, Continuous improvements of existing processes, Improvement of material/energy consumption, Performance Measurement.

From the main category of indicators, there was no process improvement in the manufacturing of cup so it was not included in the analysis.

Economic (s_1) → Manufacturing cost (ss_1)
Economic (s_1) → Machining performance (ss_2)
Economic (s_1) → Production efficiency (ss_3)

The manufacturing cost was assessed through unit production cost (sss_1) and actual machining cost (sss_2), with the remaining factors being not applicable to cup manufacturing. The unit production cost includes the cost of direct materials and labor. However, for both manufacturing methods, labor costs were the same and did not affect the assessment. Therefore, the unit production cost was assessed based solely on the cost of direct raw materials, which were quantitatively determined for each method in the parameter section. The manufacturing cost for the servo automatic machine was 2.12 birr per part, while the automatic tilt machine's cost was 2.20 birr per part, which contributed to the determination of the actual machining cost. Additionally, in terms of characteristics, the manufacturing cost for larger quantities was higher in vacuum forming and lower in pressure forming, or vice versa.

The machining performance was analyzed through cutting quality (sss_3) and surface roughness (sss_4). Cutting quality is directly related to the friction between the sheet and pre-stretching plug during the production process, which is higher in vacuum forming. The nature of the raw material during operation was also assessed in relation to surface roughness. It is generally observed that material distribution is better in pressure forming, resulting in smoother surface products, meaning surface roughness is higher in vacuum forming.

Production efficiency was evaluated through production rate (sss_5) and cutting power (sss_6). Vacuum forming machines are commonly used for large-scale production runs because they are faster and can handle larger sheets of plastic, while pressure-forming machines are typically used for small-scale production runs or more delicate applications, as they offer greater control over the shaping process [57, 58]. The manufacturing time for the automatic servo machine was 13,560 pieces per hour, compared to 11,340 pieces per hour for the automatic tilt machine. Thus, production rate was assessed based on production scale and manufacturing time. The power consumption for the servo and tilt machines was 90 kW and 150 kW, respectively. In addition to power consumption, the required shaping forces were another factor in assessing cutting power, with the force being lower in vacuum forming.

3.4.1.2. Environmental

One of the primary roles of sustainability assessments in manufacturing organizations is to minimize the negative environmental impact. To create a sustainable product and reduce this impact, assessing the manufacturing method using selective indicators is one of the most effective approaches [67]. After deciding to assess the environmental performance of plastic cups using indicators, a selective review of environmental indicators was conducted [16, 22-31]. These indicators were then organized into the corresponding categories, as shown in Table 3.6:

Table 3.6: Lists of indicators under environmental dimension

Energy Consumption:	Types of material:	Waste and Pollution:	Water Consumption:
Energy consumed, Renewable and non-renewable resource consumed, Idle energy, Energy Intensity.	Raw materials, Material composition, Usability of hazardous material, re-usability, Packaging, recyclability, Distance from source.	Waste Management, Weight of release from production process, Climate effect, reuse ratio, Pollution impact on ozone layer, Wastage and Spill over during production, Mass of coolant loss, Weight of transfers to sewage from production process.	Water Intensity, Amount of re used water, Consumption of water per unit of output, Source of water for the process. Government Rules and Regulation: Existing Environmental Regulations, Land usage.

Among the main categories of indicators, there were no government regulations affecting the manufacturing of plastic cups. Additionally, water consumption and the source of water were the same for both methods, so these factors were not included in the analysis.

Environmental (s_2) → Energy consumption (ss_4)
Environmental (s_2) → Type of material (ss_5)
Environmental (s_2) → Waste and pollution (ss_6)

The primary indicator for energy consumption in the cup manufacturing process was energy consumption by the machine (sss_7). The automatic servo cup-making machine consumed 90 kW, while the automatic tilt cup-making machine consumed 150 kW of energy.

Similarly, the type of material used was assessed through raw material (sss_8) and material composition (sss_9). The overall amount of raw material required to produce a single product was estimated by considering the weight of a single product, including the waste per part produced using each manufacturing method. Both production methods used polypropylene as the material, which was evaluated in terms of its availability in the market.

Lastly, waste and pollution were evaluated using waste management (sss_{10}) and the weight of release (sss_{11}). The weight of release from production for each method was determined by recording data from the machine over consecutive days. Additionally, the automatic tilt cup-making machine exhibited a better waste management mechanism, such as sound dampening, compared to the automatic servo cup-making machine.

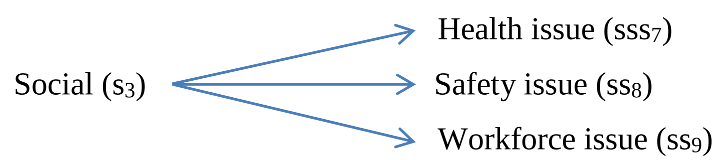
3.4.1.3. Social

Health is a critical issue for human well-being; without health, there is no life. The social impact of manufacturing operations includes health and safety concerns, which are essential aspects of sustainability. Many authors have assessed the sustainability performance of manufacturing operations by evaluating indicators related to the social pillar. These indicators are used to measure how manufacturing processes affect societal well-being. A review by [16, 22-31] identifies key indicators for creating sustainable products within the social dimension. These indicators are categorized and presented in Table 3.7.

Table 3.7: Lists of indicators under social dimension

Health Issues:	Safety Issues:	Labor Issues:	Workforce Training:
Worker Health, Noise Level, Health related absenteeism rate, Compliance with regulatory requirements imposed, Admitted level of emissions and waste from machining operations.	Worker Safety, Exposure to toxic chemicals, Near Misses, Exposure to high-energy components, Number of occupational accidents, Risk Level, Ergonomic Design.	Labor Relations, Hourly Wages, Working Hours, Workload, Community Engagement, Local Employment,	Training and Education, Average Number of Hours of training per operator, Required Skill Level.

Labor issues were not included in the main categories of indicators, as they are consistent across both methods used in the manufacturing of the cup.



In this scheme, the health issue was assessed through worker health (sss_{12}), while other factors were not directly impactful. The automatic servo cup-making machine produced visible exhaust gases, which posed a health risk for workers. However, the exhaust from the automatic tilt machine was addressed by developing a mechanism to remove it.

Similarly, safety issues were assessed through worker safety (sss_{13}) and near misses (sss_{14}). Workforce training was evaluated through training and education (sss_{15}) for operators or technicians. The automatic servo cup-making machines use negative pressure to draw in raw materials [57], which creates near-miss situations for workers and leads to safety concerns during production. Because the production speed is high in vacuum forming, the probability of near misses is greater compared to pressure forming.

3.4.2 AHP Hierarchy

Before the assessment began, the chosen indicators were correctly arranged using the MCDM (Multi-Criteria Decision-Making) structuring technique. To assess the sustainability performance of the two cup manufacturing methods, all the selected indicators were briefly discussed in terms of their impact on sustainability, as well as the feasibility of collecting appropriate data for the objectives of the investigation. For the sake of the overall assessment, the issue was broken down into a hierarchy of sustainability, as shown in Fig. 3.10 (AHP tree below), which served as the basis for pairwise comparisons at each level.

In addition to the two plastic production methods, the model or AHP hierarchy includes another production method, injection molding. While not used by the case study company, injection molding is a widely recommended method for producing plastic cups. The assessment process begins with pairwise comparisons, followed by consistency verification and detailed explanations of each indicator's contribution to the final result, along with a discussion and analysis.

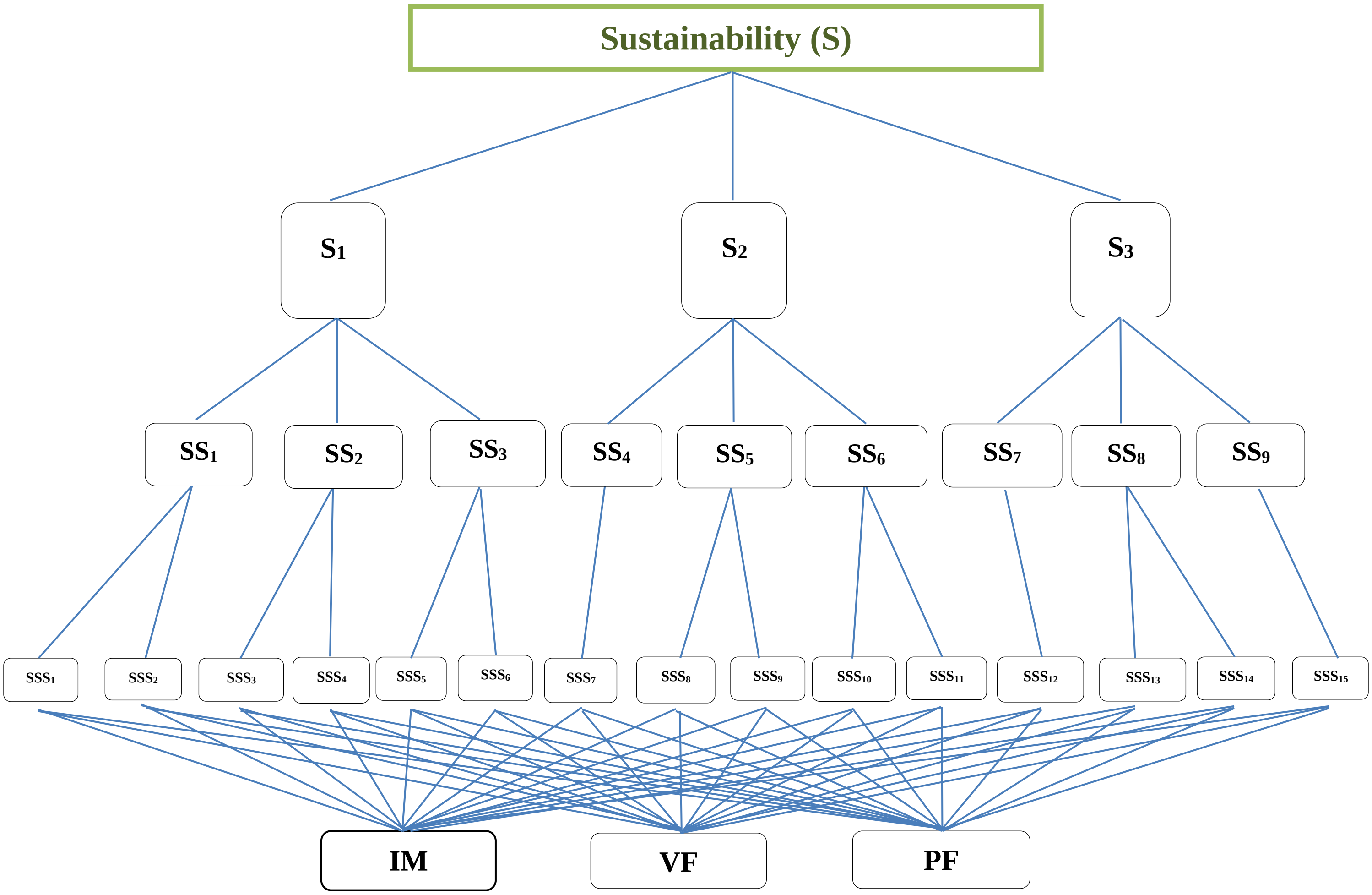


Fig 3.10: AHP Hierarchy

The fundamental comparison scale, shown in Table 3.8 below, was used to determine the comparison values for each indicator during the pairwise assessment. This predefined Saaty comparison scale (a nine-point scale) represents a fundamental set of values, which has been validated for effectiveness both empirically and theoretically. These scales are used to quantify how much more important one alternative is compared to others. The AHP approach employs these predefined Saaty scales for assessing the alternatives [61].

Table 3.8: Fundamental comparison scale [61]

Intensity	Reciprocals	Definition	Explanation
9	1/9	Extreme importance	The evidence of favoring one activity over another is of the highest possible order of affirmation
7	1/7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
5	1/5	Essential or strong importance	Experience and judgment strongly favor one activity over another
3	1/3	Moderate importance of one over another	Experience and judgment moderate favor one activity over another
1		Equal importance	Two activities contribute equally to the Objective
$\left.\begin{matrix}2\\4\\6\\8\end{matrix}\right\}$ *Intermediate values between the two adjacent judgments* *Reciprocals: If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.*			

Based on the assessment, pairwise comparison judgments proposed by decision-makers were applied to each indicator, using data regarding the alternatives. Approaches for adapting data collected from the manufactured products were carried out. In line with the desired goals of the sustainability performance assessment, decision-makers evaluated each parameter within the AHP hierarchy. The AHP analysis was performed through a step-by-step evaluation of the scores for each parameter across all four levels. Therefore, the next section briefly presents the pairwise comparison assessment within their respective goals.

3.4.2.1 Technical evaluations of the manufacturing methods

Using the developed model, a detailed technical evaluation of the three manufacturing methods—Injection Molding, Vacuum Forming, and Pressure Forming—is provided. The evaluation categorizes these methods based on the economic, environmental, and social dimensions. Each method is analyzed in relation to various factors within these categories [71-75].

1. **Economic Dimension:** includes factors such as cost efficiency, material usage, production rate, and operator skill requirements, all of which influence the overall financial viability of each manufacturing method [71-75].

➢ Injection Molding [71 - 75]:

- ✓ Production Cost / Material Cost: Low material cost per part for high-volume production, but high initial setup costs for mold creation. Economies of scale make it cost-effective for large quantities.

- ✓ Actual Manufacturing Cost / Per Part Cost: Low per-part cost at high production volumes. However, it is less cost-effective for small runs due to the expensive mold setup.

- ✓ Production Rate: High production rate with rapid cycle times, making it ideal for mass production.

- ✓ Raw Material Usage: Very efficient in material usage, with minimal scrap.

- ✓ Waste Management: Minimal waste, as most material is used for the final part.

- ✓ Operator and Technician Skills: Requires highly skilled operators and technicians for setup and machine operation, resulting in higher labor costs.

➢ Vacuum Forming [71 - 75]:

- ✧ Production Cost / Material Cost: Moderate material costs with lower initial setup costs compared to injection molding. It is ideal for small to medium production runs.

- ✧ Actual Manufacturing Cost / Per Part Cost: Moderate per-part cost. It is more cost-effective for small batches than injection molding but less efficient for large volumes.

- ✧ Production Rate: Moderate production rate with slower cycle times compared to injection molding.
- ✧ Raw Material Usage: Higher material waste due to the stretching of the material.
- ✧ Waste Management: More waste compared to injection molding, as excess material around the edges of the formed parts is discarded.
- ✧ Operator and Technician Skills: Requires less specialized skill than injection molding, leading to lower labor costs.

➢ Pressure Forming [71-75]:

- ✓ Production Cost / Material Cost: Similar to vacuum forming but typically higher, as it requires more energy and time for setup.
- ✓ Actual Manufacturing Cost / Per Part Cost: Higher per-part cost compared to both vacuum and injection molding, making it less cost-effective for large runs.
- ✓ Production Rate: Slower production rates than both injection molding and vacuum forming.
- ✓ Raw Material Usage: Moderate material waste compared to vacuum forming.
- ✓ Waste Management: Waste is generated due to excess material around the formed part.
- ✓ Operator and Technician Skills: Requires a moderate skill level for setup and operation, resulting in moderate labor costs.

2. **Environmental Dimension**

The environmental dimension focuses on factors such as energy consumption, waste generation, and raw material usage, all of which contribute to the ecological footprint of the manufacturing process [71-75].

❖ Injection Molding [71 - 75]:

- ✓ Energy Consumption: High energy consumption due to heating, injection, and cooling cycles, which increases the carbon footprint of the process.

- ✓ Raw Material Usage: Highly efficient material usage with minimal waste, reducing the need for raw material extraction.
- ✓ Waste Management: Generates minimal waste compared to other methods, reducing the overall environmental impact.
- ✓ Material Composition: Injection molding can utilize a wide variety of materials, including recycled plastics, making it potentially more environmentally friendly.

❖ Vacuum Forming [71 - 75]:

- ✧ Energy Consumption: Moderate energy consumption compared to injection molding. It involves heating and forming but doesn't require high pressure or extensive cooling.
- ✧ Raw Material Usage: Less efficient in material usage than injection molding, as excess material is discarded, contributing to higher waste.
- ✧ Waste Management: More waste is generated due to the stretching and trimming of the material, leading to a higher environmental impact.
- ✧ Material Composition: Primarily limited to thermoplastics, which may not be as environmentally friendly unless recycled materials are used [71-75].

❖ Pressure Forming [71 -75]:

- ✓ Energy Consumption: Moderate energy consumption, typically higher than vacuum forming but lower than injection molding. The additional energy is used to generate the high pressure required for forming.
- ✓ Raw Material Usage: Moderate material efficiency, with some waste generated during the forming process.
- ✓ Waste Management: Similar to vacuum forming, pressure forming produces waste, but the process can be more manageable if optimized.

- ✓ Material Composition: Like vacuum forming, pressure forming is typically limited to thermoplastics, which can be harmful to the environment if not recycled properly.

3. **Social Dimension**

The social dimension evaluates factors related to worker health and safety, worker skills, and product quality. These factors influence both the well-being of the workforce and the quality of the manufactured products [71-75].

- ➢ Injection Molding [71 - 75]:
  - ✓ Worker Health and Safety: High safety risks due to the high temperatures and pressures involved. However, modern machinery includes safety features to mitigate these risks.
  - ✓ Near Misses: Fewer near misses due to automated processes, although the complexity of setup and maintenance still poses risks if not handled properly.
  - ✓ Operator and Technician Skills: Requires skilled labor, which can lead to higher wages and labor costs, but also provides specialized employment opportunities.
  - ✓ Cutting Quality: Provides the highest level of precision and cutting quality, resulting in high-quality products.
- ➢ Vacuum Forming [71 - 75]:
  - ✧ Worker Health and Safety: Lower health risks compared to injection molding, but workers still handle heated materials, which can cause burns or injuries if safety protocols are not followed.
  - ✧ Near Misses: Fewer near misses compared to injection molding, but safety concerns exist due to the handling of hot materials.
  - ✧ Operator and Technician Skills: Requires less specialized skill compared to injection molding, leading to lower labor costs. However, workers still need training in material handling and machine operation.

- ✧ Cutting Quality: Lower cutting quality than injection molding, but still sufficient for many applications. The surface finish is not as smooth or precise.

- ➢ Pressure Forming [71 - 75]:

  - ✓ Worker Health and Safety: Higher safety risks compared to vacuum forming, particularly due to the high pressures involved in the process. Proper safety protocols are essential to avoid accidents.

  - ✓ Near Misses: More near misses than vacuum forming, due to the high-pressure conditions. Safety mechanisms are necessary to prevent accidents.

  - ✓ Operator and Technician Skills: Requires a moderate level of operator skill, leading to moderate labor costs. More training is needed compared to vacuum forming.

  - ✓ Cutting Quality: Provides better cutting quality than vacuum forming, but not as high as injection molding. The process is suitable for parts requiring greater detail or specific material properties.

3.4.3 Pair-wise Comparisons

At the top of the AHP hierarchy, the pairwise comparison starts from s_1 to s_3 within the sustainability goal. During the pairwise comparison, priorities are set for the alternatives, which is a prerequisite for assigning values for assessment. In the case of cup manufacturing, based on the available data from the company, the product is more affected by environmental parameters (e.g., waste/pollution, material, and energy consumption) than by economic parameters, such as overall cost, manufacturing cost, machining performance, and production efficiency. As a result, the environmental and economic factors are given twice the importance in the assessment.

Similarly, the available information suggests that the environmental and social factors have an intermediate assessment value, falling between moderate favor and strong favor, within the sustainability goal. In contrast, the economic factors are deemed twice as important as the social factors in the assessment.

Table 3.9: Pair -wise comparison with in a goal of sustainability

Goal	Comparison	Priority	Assessment	Explanation
S	S_1/S_2	S_2	1 / 2	Assessment value of the two production method under the three pillars were S_1=7.7, S_2=4.00, S_3=4.166 So; $\frac{S1}{S2} = \frac{7.7}{4}$ =1/1.95=0.5=1/2, $\frac{S2}{S3}=\frac{4}{4.266}$=1/0.93=1.75~2, $\frac{S1}{S3}=\frac{7.7}{4.166}=\frac{1}{1.848}=0.5=1/2$
	S_2/S_3	S_2	2	
	S_1/S_3	S_3	1 / 2	

As shown in Table 3.9 above, **s_2** has twice the importance of **s_1**, with a priority for **s_2**, and an intermediate value between moderate favor and equal importance between **s_2** and **s_3** within the sustainability goal. However, **s_1** is considered twice as important as **s_3** based on the available data within the goal of sustainability.

Following the hierarchy, the next pairwise comparison involves indicators from **ss_1** to **ss_9**, aligned with the respective goals. Manufacturing costs are the most important consideration when establishing production performance, not only for plastic products but also for all engineering products. In cup manufacturing, the cost of production, influenced by machine performance, significantly affects production efficiency. Within the economic goal, manufacturing costs were given a moderate favor assessment value compared to machining performance, while machining performance is considered seven times more important than production efficiency. Lastly, manufacturing cost is assessed as twice as important as production efficiency.

Table 3.10: Pair -wise comparison with in a goal of economic

Goal	Comparison	Priority	Assessment	Explanation
S_1	SS_1/SS_2	SS_1	3	Assessment value of the two production method under economic pillar were: SS_1=2, SS_2=0.7 and SS_3=5 So; $\frac{SS1}{SS2}=\frac{2}{0.7}$ =2.86~3, $\frac{SS2}{SS3}=\frac{0.7}{5}$ =0.14~1/7, $\frac{SS1}{SS3}=\frac{2}{5}$ = 0.4~0.5=1/2
	SS_2/SS_3	SS_3	1 / 7	
	SS_1/SS_3	SS_3	1 / 2	

As shown above Table 3.10, there were a three times important assessment value between ss_1 and ss_2, with ss_1 priority in an economic goal or objective, but ss_3 were seven times important than ss_2 with a priority ss_3. In a similar vein, there were a two times important assessment value with in ss_1 and ss_3 in a priority of ss_3.

The next corresponding pairwise comparisons were ss_4 up to ss_6 with in the objective of environment. The amount, size, availability, composition of material was the best determinant factor during manufacturing, if there were a product manufacturing energy must be consumed and waste also released. In the cup, manufacturing type of material through availability of raw material was two times favor than energy consumption and waste have two times important assessment value than type of material and lastly the waste has three times importance than energy consumption.

Table 3.11: Pair -wise comparison with in a goal of environment

Goal	Comparison	Priority	Assessment	Explanation
S_2	SS_4/SS_5	SS_5	1 / 2	Assessment value of the two methods under environment pillar were: SS_4=2, SS_5=1.25 and SS_6=0.75 So; $\frac{SS4}{SS5} = \frac{2}{1.25}$ =1/1.6=0.62~1/2, $\frac{SS5}{SS6}=\frac{1.25}{0.75}$=1/1.66=0.6~1/2, $\frac{SS4}{SS6}=\frac{2}{0.75} = \frac{1}{2.66} = 0.3\sim1/3$
	SS_5/SS_6	SS_6	1 / 2	
	SS_4/SS_6	SS_6	1 / 3	

Table 3.11 briefly states that the assessment of pair -wise comparison with an objective of environment in its respective categories. There were a two times important assessment value between ss_4 and ss_5 in a priory of ss_5 similarly there were a two times important assessment value between ss_5 and ss_6 in a priory of ss_6 and finally three times important assessment value between ss_4 and ss_6 in a priory of ss_6.

From the hierarchy the next pair -wise comparison were ss_7 up to ss_9 with the objective of social impact for sustainability. Either the health or the safety issue has been very necessary in the manufacturing operation including the qualifications of the worker. In the cup manufacturing, all the machines were automatic and it highly expose for health and safety issue for the worker but it become minimize by training and education. Due to this the health and safety issue were equal importance assessment with each other and the workforce issue were three times important than safety issue also the workforce issue becomes nine times important than health issue assessment with in the objective of social.

Table 3.12: Pair -wise comparison with in a goal of social

Goal	Comparison	Priority	Assessment	Explanation
S_3	SS_7/SS_8	SS_7/SS_8	1	Assessment value of the two manufacturing method under social pillar were: SS_7=0.333, SS_8=0.833 and SS_9=3 So; $\frac{SS7}{SS8}=\frac{0.33}{0.83}$ =0.93~1, $\frac{SS8}{SS9}=\frac{0.833}{3}$=0.3~1/3, $\frac{SS7}{SS9}=\frac{0.3}{3}$ = 0.1~1/9
	SS_8/SS_9	SS_9	1/3	
	SS_7/SS_9	SS_9	1/9	

As shown above Table 3.12 there were an equal importance assessment between ss_7 and ss_8 with in a social goal or objective and with the same way ss_9 were three times important than ss_8 also ss_9 nine times important than ss_7 with the objective of social factors for sustainability.

From the hierarchy the next pair wise comparison held from sss_1 up to sss_{15} with the corresponding objective. As mentioned in section 3.4 the impact and interaction of each indicator with the other and contributes to the overall study intention. For an accurate assessment of the entirety of the leakages of each indicator, a comprehensive examination of the data and the practical implications of various scientific findings conducted.

Following that, based on the available data in section 3.4.1.1, 3.4.1.2 and 3.4.1.3 with a compressive examination of it, the next Table 3.12 clearly and accurately assessed it thoroughly using observations from various circumstances.

As mentioned in section 3.4.1.1 the actual machining cost and cost of a large quantity production in the manufacturing of two methods were having a strong and dominance assessment value with the goal of manufacturing cost.

Within the same sense mentioned in section, 3.4.1.3 the energy consumption by the machine has an intermediate assessment value between strongly favor and strongly favor and dominance than raw material within the goal of energy consumption based on the information on hand.

Likewise, there was an intermediate assessment value between equal importance and moderate favor value in the worker safety and near miss within the goal of safety issue based on the indicated information in section 3.4.1.3.

Table 3.13: Pair -wise comparison of indicators with in a corresponding goal

Goal	Comparison	Priority	Assessment	Explanation
SS_1	SSS_1/SSS_2	SSS_1/SSS_2	1	$\frac{SSS1}{SSS2}=\frac{1}{1}=1$
SS_2	SSS_3/SSS_4	SSS_4	1 / 2	$\frac{SSS3}{SSS4}=\frac{1/2}{1/5}=2.5$,1/2.5 $sss_3 = sss_4$ ~1/2
SS_3	SSS_5/SSS_6	SSS_6	1 / 2	$\frac{SSS5}{SSS6}=\frac{2}{3}=0.66$ ~1/2, $sss_6=2sss_5$
SS_4	SSS_7/SSS_8	SSS_7	8	$\frac{SSS7}{SSS8}=\frac{2}{1/4}=8$
	SSS_8/SSS_9	SSS_9	1 / 4	$\frac{SSS8}{SSS9}=\frac{1/4}{1}=1/4$
	SSS_7/SSS_9	SSS_7	2	$\frac{SSS7}{SSS9}=\frac{2}{1}=2$
SS_5	SSS_7/SSS_8	SSS_8	8	$\frac{SSS7}{SSS8}=\frac{2}{1/4}=8$
	SSS_8/SSS_9	SSS_9	1 / 4	$\frac{SSS8}{SSS9}=\frac{1/4}{1}=1/4$
	SSS_7/SSS_9	SSS_7	2	$\frac{SSS7}{SSS9}=\frac{2}{1}=2$
SS_6	SSS_{10}/SSS_{11}	SSS_{10}	2	$\frac{SSS10}{SSS11}=\frac{1/2}{1/4}=2$
SS_7	SSS_{12}/SSS_{13}	SSS_{13}	1 / 2	$\frac{SSS12}{SSS13}=\frac{1/3}{1/2}=0.6\sim1/2$
	SSS_{13}/SSS_{14}	SSS_{13}	2	$\frac{SSS13}{SSS14}=\frac{1/2}{1/3}=1.5\sim2$
	SSS_{12}/SSS_{14}	SSS_{12}/SSS_{14}	1	$\frac{SSS12}{SSS14}=\frac{1/3}{1/3}=1$
SS_8	SSS_{12}/SSS_{13}	SSS_{13}	1 / 2	$\frac{SSS12}{SSS13}=\frac{1/3}{1/2}=0.6\sim1/2$
	SSS_{13}/SSS_{14}	SSS_{13}	2	$\frac{SSS13}{SSS14}=\frac{1/2}{1/3}=1.5\sim2$
	SSS_{12}/SSS_{14}	SSS_{12}/SSS_{14}	1	$\frac{SSS12}{SSS14}=\frac{1/3}{1/3}=1$
	SSS_{14}/SSS_{15}	SSS_{15}	1 / 9	$\frac{SSS14}{SSS15}=\frac{1/3}{3}=1/9$
	SSS_{13}/SSS_{15}	SSS_{15}	1 / 6	$\frac{SSS13}{SSS15}=\frac{1/2}{3}=1/6$
SS_9	SSS_{13}/SSS_{14}	SSS_{13}	2	$\frac{SSS13}{SSS14}=\frac{1/2}{1/3}=1.5\sim2$
	SSS_{14}/SSS_{15}	SSS_{15}	1 / 9	$\frac{SSS14}{SSS15}=\frac{1/3}{3}=1/9$
	SSS_{13}/SSS_{15}	SSS_{15}	1 / 6	$\frac{SSS13}{SSS15}=\frac{1/2}{3}=1/6$

Due to the single indicator in Table 3.13 above, it was a bit difficult to judge the assessment value of the goals of ss_4, ss_7, and ss_9, but the pairwise comparison was maintained by mixing to the next indicator and then taking the goal step -by -step.

The last pairwise comparison done by the two manufacturing methods in line with their respective objectives. According to the AHP hierarchy, the two methods of producing plastic cups—vacuum forming and pressure forming—were each assessed using an objective ranging from sss_1 to sss_{15}. This assessment has used as the base for the completely pairwise comparison due to the objective of the study depends on it.

Table 3.14: Pair -wise comparison of the two methods with in a corresponding goal

Goal	VF/PF		Explanation
	Priority	Assessment	
SSS_1	VF/PF	1	VF = (67.2/67.2) PF =1
SSS_2	VF/PF	1	VF = (2.2/2.12) PF ≈ 1
SSS_3	PF	1 / 2	VF = (180/120) PF=1/1.5 ≈ ½
SSS_4	PF	1 / 5	VF=1/5PF material distribution ≈ 5
SSS_5	VF	2	VF = (11340/13560) PF + VF recommend for large scale production =0.84 + 1.5 ≈ 2
SSS_6	VF	3	VF = (150/90) KW PF + Required shaping force (1.5) = 3.16 ≈ 3
SSS_7	VF	2	VF = 1.667PF (Energy consumption ratio) ≈ 2
SSS_8	PF	1 / 4	VF = (0.005/0.005) PF (Product weight ratio) and VF = (0.047/0.01456) PF (Waste ratio) ≈ 1/4
SSS_9	VF/PF	1	VF = (67.2/67.2) PF - Material composition and availability with cost ≈ 1
SSS_{10}	PF	1 / 2	VF = (Damping and exhaust removed mechanisms) PF ≈1/2
SSS_{11}	PF	1 / 4	VF = (0.047/0.01456) PF=3.228≈1/4
SSS_{12}	PF	1 / 3	VF = (Exhaust gas removed and use positive pressure and also minimum work risk) PF≈1/3
SSS_{13}	PF	1 / 2	VF (causes safety issue due to negative pressure to suck material) = PF ≈ 1/2
SSS_{14}	PF	1 / 3	VF (Expose for near misses due to production speed, negative pressure and less training) = PF ≈ 1/3
SSS_{15}	VF	3	VF = (8/6) PF for Operator and VF = (10/8) PF for Technician = 1.333+1.25=2.83 ≈ 3

Table 3.15: Pair -wise comparison of the two methods with in a corresponding goal

Goal	IM/TF		Explanation
	Priority	Assessment	
SSS_1	IM/TF	1	IM = (3.85/4) TF =1
SSS_2	IM	3	IM = (0.2/0.06) TF ≈ 3
SSS_3	IM	5	IM = (5)TF=5
SSS_4	TF	1 / 2	IM=1/2TF surface roughness ratio
SSS_5	TF	1 / 6	IM (55000/9000) = TF
SSS_6	TF	1 / 3	IM = (1/3) TF Cutting power requirement ratio
SSS_7	TF	1 / 2	IM =3.5/6.5TF (Energy consumption ratio) ≈0.5
SSS_8	IM/PF	1	IM = (the same take an assumption)TF - Material composition and availability with cost ≈ 1
SSS_9	IM/TF	1	IM = (the same take an assumption)TF - Material composition and availability with cost ≈ 1
SSS_{10}	IM	5	IM = (waste ratio) TF ≈5
SSS_{11}	IM	7	IM = (10/1.5) PF≈7
SSS_{12}	TF	1 / 3	IM = (Ratio of exposer of hazards) TF≈1/3
SSS_{13}	TF	1 / 8	VF (causes safety issue due to higher safety risks due to complexity of machine) = TF ≈ 1/8
SSS_{14}	TF	1 / 2	IM (Expose for near misses) = PF ≈ 1/2
SSS_{15}	VF	5	IM = (high Operator and technician skills) TF ≈ 5

3.4.4 Judgment Matrix

Judgment matrix has formulated at every level of the AHP hierarchy; and it must pass the consistency verification test, which briefly present in the next section 3.4.5. However, the focus of this section is on formulating the judgment matrix of contribution of each indicator with respect to the manufacturing method separately due to for getting clear and proper input information for result and discussion section.

$$\begin{bmatrix} VF & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1 \\ SSS2 & 1 & 1 & 2 \\ SSS3 & 1 & 1/2 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1/2 \\ SSS2 & 1 & 1 & 1 \\ SSS3 & 2 & 1 & 1 \end{bmatrix}$$

- $\frac{SSS1}{SSS1} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS1}{SSS2} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

- $\frac{SSS1}{SSS3} = \frac{VF}{PF} = \frac{1}{1/2}$, So the assessment value for VF=1 and for PF =1/2.
- $\frac{SSS2}{SSS1}$ = Reciprocal of $\frac{SSS1}{SSS2}$, so the assessment value for VF=1 and for PF = 1.
- $\frac{SSS2}{SSS2} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS2}{SSS3} = \frac{VF}{PF} = \frac{1}{1/2} = \frac{2}{1}$, So, the assessment value for VF=2 and for PF = 1.
- $\frac{SSS3}{SSS1}$ = Reciprocal of $\frac{SSS1}{SSS3}$, so the assessment value for VF=1 and for PF = 2.
- $\frac{SSS3}{SSS2}$ = Reciprocal of $\frac{SSS2}{SSS3}$, so the assessment value for VF=1/2 and for PF = 1.
- $\frac{SSS3}{SSS3} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 3 & 1 \\ SSS4 & 1/3 & 1 & 1 \\ SSS5 & 1 & 1 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 1 & 4 \\ SSS4 & 1 & 1 & 9 \\ SSS5 & 1/4 & 1/9 & 1 \end{bmatrix}$$

- $\frac{SSS3}{SSS3} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS3}{SSS4} = \frac{VF}{PF} = \frac{1/2}{1/5} = 3/1$, So, the assessment value for VF=3 and PF=1.
- $\frac{SSS3}{SSS5} = \frac{VF}{PF} = \frac{1/2}{2} = 1/4$, So, the assessment value for VF=1 and PF=4.
- $\frac{SSS4}{SSS3}$ = Reciprocal of $\frac{SSS3}{SSS4}$, so the assessment value for VF=1/3 and for PF = 1.
- $\frac{SSS4}{SSS4} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS4}{SSS5} = \frac{VF}{PF} = \frac{1/5}{2} = 0.1 = 1/9$, So, the assessment value for VF=1 and PF=9.
- $\frac{SSS5}{SSS3}$ = Reciprocal of $\frac{SSS3}{SSS5}$, so the assessment value for VF=1 and for PF = 1/4.
- $\frac{SSS5}{SSS4}$ = Reciprocal of $\frac{SSS4}{SSS5}$, so the assessment value for VF=1 and for PF = 1/9.
- $\frac{SSS5}{SSS5} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 1 & 1 \\ SSS5 & 1 & 1 & 2 \\ SSS6 & 1 & 1/2 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 9 & 9 \\ SSS5 & 1/9 & 1 & 3 \\ SSS6 & 1/9 & 1/3 & 1 \end{bmatrix}$$

- $\frac{SSS4}{SSS4} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS4}{SSS5} = \frac{VF}{PF} = \frac{1/5}{2} = \frac{1}{10} = 0.1 = 1/9$, So, the assessment value for VF=1 and PF=9.
- $\frac{SSS4}{SSS6} = \frac{VF}{PF} = \frac{1/5}{3} = \frac{1}{15} = 0.067 \sim 0.1 = 1/9$, So, the assessment value for VF=1 and PF=9.

- $\frac{SSS5}{SSS4}$ = Reciprocal of $\frac{SSS4}{SSS5}$, so the assessment value for VF=1 and for PF = 1/9.
- $\frac{SSS5}{SSS5} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS5}{SSS6} = \frac{VF}{PF} = \frac{2}{3}$, So, the assessment value for VF=2 and PF=3.
- $\frac{SSS6}{SSS4}$ = Reciprocal of $\frac{SSS4}{SSS6}$, so the assessment value for VF=1 and for PF = 1/9.
- $\frac{SSS6}{SSS5}$ = Reciprocal of $\frac{SSS5}{SSS6}$, so the assessment value for VF=1/2 and for PF = 1/3.
- $\frac{SSS6}{SSS6} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1 & 1 \\ SSS8 & 1 & 1 & 2 \\ SSS9 & 1 & 1/2 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1/8 & 1/2 \\ SSS8 & 8 & 1 & 8 \\ SSS9 & 2 & 1/8 & 1 \end{bmatrix}$$

- $\frac{SSS7}{SSS7} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS7}{SSS8} = \frac{VF}{PF} = \frac{2}{1/4} = \frac{1}{1/8} =$, So, the assessment value for VF=1 and PF=1/8.
- $\frac{SSS7}{SSS9} = \frac{VF}{PF} = \frac{2}{1} = \frac{1}{1/2}$, So, the assessment value for VF=1 and PF=1/2.
- $\frac{SSS8}{SSS7}$ = Reciprocal of $\frac{SSS7}{SSS8}$, so the assessment value for VF=1 and for PF = 8.
- $\frac{SSS8}{SSS8} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS8}{SSS9} = \frac{VF}{PF} = \frac{1}{4} = \frac{2}{8}$, So, the assessment value for VF=2 and PF=8.
- $\frac{SSS9}{SSS7}$ = Reciprocal of $\frac{SSS7}{SSS9}$, so the assessment value for VF=1 and for PF = 2.
- $\frac{SSS9}{SSS8}$ = Reciprocal of $\frac{SSS8}{SSS9}$, so the assessment value for VF=1/2 and for PF = 1/8.
- $\frac{SSS9}{SSS9} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1/4 & 1/4 \\ SSS9 & 4 & 1 & 2 \\ SSS10 & 4 & 1/2 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1 & 1/2 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 2 & 1 & 1 \end{bmatrix}$$

- $\frac{SSS8}{SSS8} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS8}{SSS9} = \frac{VF}{PF} = \frac{1/4}{1}$, So, the assessment value for VF=1/4 and PF=1.
- $\frac{SSS8}{SSS10} = \frac{VF}{PF} = \frac{1/4}{1/2}$, So, the assessment value for VF=1/4 and PF=1/2.
- $\frac{SSS9}{SSS8}$ = Reciprocal of $\frac{SSS8}{SSS9}$, so the assessment value for VF=4 and for PF = 1.

- $\frac{SSS9}{SSS9} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS9}{SSS10} = \frac{VF}{PF} = \frac{1}{1/2} = \frac{2}{1}$, So, the assessment value for VF=2 and PF=1.
- $\frac{SSS10}{SSS8}$ = Reciprocal of $\frac{SSS8}{SSS10}$, so the assessment value for VF=4 and for PF = 2.
- $\frac{SSS10}{SSS9}$ = Reciprocal of $\frac{SSS9}{SSS10}$, so the assessment value for VF=1/2 and for PF = 1.
- $\frac{SSS10}{SSS10} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 1 & 1 & 2 \\ SSS11 & 1 & 1/2 & 1 \end{bmatrix} \qquad \begin{bmatrix} VF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 1/2 & 1/4 \\ SSS10 & 2 & 1 & 1 \\ SSS11 & 4 & 1 & 1 \end{bmatrix}$$

- $\frac{SSS9}{SSS9} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS9}{SSS10} = \frac{VF}{PF} = \frac{1}{1/2}$, So, the assessment value for VF=1 and PF=1/2.
- $\frac{SSS9}{SSS11} = \frac{VF}{PF} = \frac{1}{1/4}$, So, the assessment value for VF=1 and PF=1/4.
- $\frac{SSS10}{SSS9}$ = Reciprocal of $\frac{SSS9}{SSS10}$, so the assessment value for VF=1 and for PF = 2.
- $\frac{SSS10}{SSS10} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS10}{SSS11} = \frac{VF}{PF} = \frac{1/2}{1/4} = \frac{2}{1}$, so, the assessment value for VF=2 and for PF = 1.
- $\frac{SSS11}{SSS9}$ = Reciprocal of $\frac{SSS9}{SSS11}$, so the assessment value for VF=1 and for PF = 4.
- $\frac{SSS11}{SSS10}$ = Reciprocal of $\frac{SSS10}{SSS11}$, so the assessment value for VF=1/2 and for PF = 1.
- $\frac{SSS11}{SSS11} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 9 & 8 \\ SSS13 & 1/9 & 1 & 3 \\ SSS14 & 1/8 & 1/3 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 7 & 6 \\ SSS13 & 1/7 & 1 & 2 \\ SSS14 & 1/6 & 1/2 & 1 \end{bmatrix}$$

- $\frac{SSS12}{SSS12} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS12}{SSS13} = \frac{VF}{PF} = \frac{1/3}{1/2}$, the assessment value for VF=1/3 and PF=1/2.
- $\frac{SSS12}{SSS14} = \frac{VF}{PF} = \frac{1/3}{1/3}$, the assessment value for VF=1/3 and PF=1/3.
- $\frac{SSS13}{SSS12}$ = Reciprocal of $\frac{SSS12}{SSS13}$, so the assessment value for VF=3 and for PF = 2.

- $\frac{SSS13}{SSS13} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS13}{SSS14} = \frac{VF}{PF} = \frac{1/2}{1/3}$, the assessment value for VF=1/2 and for PF = 1/3.
- $\frac{SSS14}{SSS12}$ = Reciprocal of $\frac{SSS12}{SSS14}$, so the assessment value for VF=3 and for PF = 3.
- $\frac{SSS14}{SSS13}$ = Reciprocal of $\frac{SSS13}{SSS14}$, so the assessment value for VF=2 and for PF = 3.
- $\frac{SSS14}{SSS14} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

$$\begin{bmatrix} VF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 3 & 1 \\ SSS14 & 1/3 & 1 & 1 \\ SSS15 & 1 & 1 & 1 \end{bmatrix} \qquad \begin{bmatrix} PF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 2 & 6 \\ SSS14 & 1/2 & 1 & 9 \\ SSS15 & 1/6 & 1/9 & 1 \end{bmatrix}$$

- $\frac{SSS13}{SSS13} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS13}{SSS14} = \frac{VF}{PF} = \frac{1/2}{1/3} = \frac{3}{2}$, the assessment value for VF=3 and PF=2.
- $\frac{SSS13}{SSS15} = \frac{VF}{PF} = \frac{1/2}{3} = \frac{1}{6}$, the assessment value for VF=1 and PF=6.
- $\frac{SSS14}{SSS13}$ = Reciprocal of $\frac{SSS13}{SSS14}$, so the assessment value for VF=1/3 and for PF = 1/2.
- $\frac{SSS14}{SSS14} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.
- $\frac{SSS14}{SSS15} = \frac{VF}{PF} = \frac{1/3}{3} = \frac{1}{9}$, the assessment value for VF=1 and for PF = 9.
- $\frac{SSS15}{SSS13}$ = Reciprocal of $\frac{SSS13}{SSS15}$, so the assessment value for VF=1 and for PF =1/6.
- $\frac{SSS15}{SSS14}$ = Reciprocal of $\frac{SSS14}{SSS15}$, so the assessment value for VF=1 and for PF = 1/9.
- $\frac{SSS15}{SSS15} = \frac{VF}{PF} = 1$, Due to equal favor the assessment value for VF=1 and PF=1.

3.4.5 Analyze AHP Consistency

When paired comparisons made for n variables, the judgment matrix (A) formed. For each entry in the matrix, a_{ij}, the matrix was created by comparing the elements of row Ai with the corresponding elements of column A_j so that A = (a_{ij}), where i = 1, 2… n and j = 1, 2… n represent the number of indicators as shown in equation (1) [63].

$$A_{matrix}=\begin{bmatrix} 1 & a12 & \ldots & a1n \\ a21 & \ldots & aij & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ an1 & \ldots & \ldots & 1 \end{bmatrix} \qquad aij=1,\ \forall_{i,j}=1,\ \text{els } aij= {}^{1}/_{aij} \quad \ldots\ldots (1)[63]$$

The judgment matrix for indicators must normalized to obtain the weights for each indicator. Each matrix value divided over the column total where it belongs. Then, the rows of all the standardized values (w_{aij}) were summed and divided by the number of indicators obtaining the weighting for each indicator (Wi) as shown in equation (2) [63].

$$A_{normalized}=\begin{bmatrix} 1 & w12 & \dots & w1n \\ w21 & \dots & wij & \dots \\ \dots & \dots & \dots & \dots \\ wn1 & \dots & \dots & 1 \end{bmatrix} \quad \mathrm{Wij} = {aij}/{\sum_i^n aij} \quad \text{.................................... (2)[63]}$$

Once the judgment matrix A were completed, the problem becomes a problem of weight vectors and eigenvalues: Aw = λw, where A is the normalized matrix of pairwise comparisons, w is the eigenvector that represents the ranking or priority order, and λ is the maximum eigenvalue representing a consistency measure of the judgments as shown in equation (3)(4) [62].

$$Wi=\begin{bmatrix} W1 \\ \dots \\ \dots \\ Wn \end{bmatrix}, \; Wi={\sum_i^n Wi1}/{n} \quad \text{.................................... (3)[63]}$$

$$\lambda_{max}=\sum_1^n {Wi}/{Wij} \quad \text{.................................... (4)[63]}$$

It has been necessary to calculate the consistency ratio (CR) proposed by Saaty to verify the consistency of the AHP. As shown in Equation 6 below, this ratio based on a consistency index (CI) and average consistency index (RI). For consistency verification, the average consistency index proposed by [69] utilized as reported in Table 3.16 [62].

$$CI = {\lambda max - n}/{n-1} \quad \text{.................................... (5)[63]}$$

$$\mathrm{CR}= {CI}/{RI} \quad \text{.................................... (6)[63]}$$

Table 3.16: Average consistency index [69].

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

If CR < 0.10, the consistency was reasonable, whereas if the CR > 0.10, the hierarchical analysis model was inconsistent, and the preference assignment and pairwise comparisons must be performed again to obtain a reliable indicator weighing model.

- Verify consistency of pairwise comparison matrix S_1 through S_3 within the goal of S.

Amatrix = $\begin{bmatrix} S & S1 & S2 & S3 \\ S1 & 1 & 1/2 & 1/2 \\ S2 & 2 & 1 & 2 \\ S3 & 2 & 1/2 & 1 \end{bmatrix}$ Change into decimal $\begin{bmatrix} S & S1 & S2 & S3 \\ S1 & 1 & 0.5 & 0.5 \\ S2 & 2 & 1 & 2 \\ S3 & 2 & 0.5 & 1 \end{bmatrix}$

$$\begin{bmatrix} S & S1 & S2 & S3 \\ S1 & 1 & 0.5 & 0.5 \\ S2 & 2 & 1 & 2 \\ S3 & 2 & 0.5 & 1 \\ SUM & 5 & 2 & 3.5 \end{bmatrix} Change\ to\ normilized\ matrix \begin{bmatrix} S & S1 & S2 & S3 \\ S1 & 1/5 & 0.5/2 & 0.5/3.5 \\ S2 & 2/5 & 1/2 & 2/3.5 \\ S3 & 2/5 & 0.5/2 & 1/3.5 \end{bmatrix}$$

Calculate indicator or criteria weight (C.W) = $\frac{\sum Wi1}{n}$ $\begin{bmatrix} S & S1 & S2 & S3 & CW \\ S1 & 0.2 & 0.25 & 0.14 & 0.197 \\ S2 & 0.4 & 0.5 & 0.57 & 0.49 \\ S3 & 0.4 & 0.25 & 0.28 & 0.31 \end{bmatrix}$

Calculate consistency by using the first matrix do not use normalized matrix and multiply by criteria weight.

$$\begin{bmatrix} S & S1 & S2 & S3 \\ S1 & 0.2 * 0.197 & 0.25 * 0.49 & 0.14 * 0.31 \\ S2 & 0.4 * 0.197 & 0.5 * 0.49 & 0.57 * 0.31 \\ S3 & 0.4 * 0.197 & 0.25 * 0.49 & 0.28 * 0.31 \end{bmatrix}$$

Calculate the weighed sum value (W) = $\frac{\sum Wi1}{C.W}$= $\begin{bmatrix} S & S1 & S2 & S3 & W \\ S1 & 0.19 & 0.24 & 0.15 & 3.03 \\ S2 & 0.39 & 0.49 & 0.62 & 2.96 \\ S3 & 0.39 & 0.24 & 0.31 & 3.05 \end{bmatrix}$

Calculate the maximum eigenvalue (λ_{max}) = $\sum_1^n Wi/_n$ = $\frac{3.03+2.96+3.05}{3}$ = 3.01

Consistency index (CI) = $\frac{\lambda \max - n}{n-1}$ = 0.07844

Consistency Ratio = $\frac{CI}{RI}$ = $\frac{0.07844}{0.52}$ = 0.0150856 < 0.1

- Verify consistency of pairwise comparison matrix SS_1 through SS_3 within the goal of S_1.

Amatrix = $\begin{bmatrix} S1 & SS1 & SS2 & SS3 \\ SS1 & 1 & 3 & 1/2 \\ SS2 & 1/3 & 1 & 1/7 \\ SS3 & 2 & 7 & 1 \end{bmatrix}$ Change into decimal $\begin{bmatrix} S1 & SS1 & SS2 & SS3 \\ SS1 & 1 & 3 & 0.5 \\ SS2 & 0.33 & 1 & 0.14 \\ SS3 & 2 & 7 & 1 \end{bmatrix}$

$\begin{bmatrix} S1 & SS1 & SS2 & SS3 \\ SS1 & 1 & 3 & 0.5 \\ SS2 & 0.33 & 1 & 0.14 \\ SS3 & 2 & 7 & 1 \\ SUM & 3.3 & 11 & 1.64 \end{bmatrix} Change\ to\ normilized\ matrix \begin{bmatrix} S1 & SS1 & SS2 & SS3 \\ SS1 & 0.3 & 0.27 & 0.3 \\ SS2 & 0.1 & 0.09 & 0.08 \\ SS3 & 0.6 & 0.63 & 0.60 \end{bmatrix}$

Calculate criteria weight (C.W) = $\frac{\sum Wi1}{n}$

$\begin{bmatrix} S1 & SS1 & SS2 & SS3 & CW \\ SS1 & 0.3 & 0.27 & 0.3 & 0.29 \\ SS2 & 0.1 & 0.09 & 0.08 & 0.09 \\ SS3 & 0.6 & 0.63 & 0.60 & 0.60 \end{bmatrix}$

Calculate consistency by using the first matrix do not use normalized matrix and multiply by criteria weight.

$\begin{bmatrix} S1 & SS1 & SS2 & SS3 \\ SS1 & 0.3 * 0.29 & 0.27 * 0.09 & 0.3 * 0.60 \\ SS2 & 0.1 * 0.29 & 0.09 * 0.09 & 0.08 * 0.60 \\ SS3 & 0.6 * 0.29 & 0.63 * 0.09 & 0.60 * 0.60 \end{bmatrix}$

Calculate the weighed sum value (W) = $\frac{\sum Wi1}{C.W} = \begin{bmatrix} S1 & SS1 & SS2 & SS3 & W \\ SS1 & 0.29 & 0.27 & 0.3 & 3.0 \\ SS2 & 0.097 & 0.09 & 0.08 & 3.06 \\ SS3 & 0.58 & 0.64 & 0.61 & 3.004 \end{bmatrix}$

Calculate the maximum eigenvalue (λ_{max}) = $\sum_1^n Wi/n = \frac{3.0+3.06+3.004}{3} = 3.025492$

Consistency index (CI) = $\frac{\lambda \max - n}{n-1}$ = 0.012746

Consistency Ratio = $\frac{CI}{RI} = \frac{0.025065}{0.52}$ = 0.0245115 < 0.1

- Verify consistency of pairwise comparison matrix SS_4 through SS_6 within the goal of S_2.

Amatrix = $\begin{bmatrix} S2 & SS4 & SS5 & SS6 \\ SS4 & 1 & 1/2 & 1/3 \\ SS5 & 2 & 1 & 1/2 \\ SS6 & 3 & 2 & 1 \end{bmatrix}$ Change into decimal $\begin{bmatrix} S2 & SS4 & SS5 & SS6 \\ SS4 & 1 & 0.5 & 0.33 \\ SS5 & 2 & 1 & 0.5 \\ SS6 & 3 & 2 & 1 \end{bmatrix}$

$$\begin{bmatrix} S2 & SS4 & SS5 & SS6 \\ SS4 & 1 & 0.5 & 0.33 \\ SS5 & 2 & 1 & 0.5 \\ SS6 & 3 & 2 & 1 \\ SUM & 6 & 3.5 & 1.83 \end{bmatrix} \text{Change to normilized matrix} \begin{bmatrix} S2 & SS4 & SS5 & SS6 \\ SS4 & 0.16 & 0.14 & 0.10 \\ SS5 & 0.33 & 0.28 & 0.27 \\ SS6 & 0.50 & 0.57 & 0.54 \end{bmatrix}$$

Calculate criteria weight (C.W) = $\frac{\sum Wi1}{n}$

$$\begin{bmatrix} S2 & SS4 & SS5 & SS6 & CW \\ SS4 & 0.16 & 0.14 & 0.10 & 0.16 \\ SS5 & 0.33 & 0.28 & 0.27 & 0.29 \\ SS6 & 0.50 & 0.57 & 0.54 & 0.54 \end{bmatrix}$$

Calculate consistency by using the first matrix do not use normalized matrix and multiply by criteria weight.

$$\begin{bmatrix} S2 & SS4 & SS5 & SS6 \\ SS4 & 0.16 & 0.14 & 0.17 \\ SS5 & 0.32 & 0.29 & 0.27 \\ SS6 & 0.49 & 0.59 & 0.54 \end{bmatrix}$$

Calculate the weighed sum value (W) = $\frac{\sum Wi1}{C.W} = \begin{bmatrix} S2 & SS4 & SS5 & SS6 & W \\ SS4 & 0.16 & 0.14 & 0.17 & 3.004 \\ SS5 & 0.32 & 0.29 & 0.27 & 3.1029 \\ SS6 & 0.49 & 0.59 & 0.54 & 3.0137 \end{bmatrix}$

Calculate the maximum eigenvalue (λ_{max}) = $\sum_1^n Wi/_n = \frac{3.004+3.1029+3.0137}{3} = 3.04025$

Consistency index (CI) = $\frac{\lambda \max - n}{n-1}$ = 0.020125

Consistency Ratio = $\frac{CI}{RI} = \frac{0.000854}{0.52}$ = 0.0387018< 0.1

- Verify consistency of pairwise comparison matrix SS_7 through SS_9 within the goal of S_3.

Amatrix = $\begin{bmatrix} S3 & SS7 & SS8 & SS9 \\ SS7 & 1 & 1 & 1/9 \\ SS8 & 1 & 1 & 1/3 \\ SS9 & 9 & 3 & 1 \end{bmatrix}$ Change into decimal $\begin{bmatrix} S3 & SS7 & SS8 & SS9 \\ SS7 & 1 & 1 & 0.11 \\ SS8 & 1 & 1 & 0.33 \\ SS9 & 9 & 3 & 1 \end{bmatrix}$

$$\begin{bmatrix} S3 & SS7 & SS8 & SS9 \\ SS7 & 1 & 1 & 0.11 \\ SS8 & 1 & 1 & 0.33 \\ SS9 & 9 & 3 & 1 \\ SUM & 11 & 5 & 1.44 \end{bmatrix} \text{Change to normilized matrix} \begin{bmatrix} S3 & SS7 & SS8 & SS9 \\ SS7 & 0.09 & 0.19 & 0.07 \\ SS8 & 0.09 & 0.19 & 0.23 \\ SS9 & 0.81 & 0.60 & 0.69 \end{bmatrix}$$

Calculate criteria weight (C.W) = $\frac{\sum Wi1}{n}$

$$\begin{bmatrix} S3 & SS7 & SS8 & SS9 & CW \\ SS7 & 0.09 & 0.19 & 0.07 & 0.12 \\ SS8 & 0.09 & 0.19 & 0.23 & 0.17 \\ SS9 & 0.81 & 0.60 & 0.69 & 0.70 \end{bmatrix}$$

Calculate consistency by using the first matrix do not use normalized matrix and multiply by criteria weight.

$$\begin{bmatrix} S3 & SS7 & SS8 & SS9 \\ SS7 & 0.12 & 0.17 & 0.07 \\ SS8 & 0.12 & 0.17 & 0.23 \\ SS9 & 1.10 & 0.52 & 0.70 \end{bmatrix}$$

Calculate the weighed sum value (W) = $\frac{\sum Wi1}{C.W}$= $\begin{bmatrix} S3 & SS7 & SS8 & SS9 & W \\ SS7 & 0.12 & 0.17 & 0.07 & 3.05 \\ SS8 & 0.12 & 0.17 & 0.23 & 2.879 \\ SS9 & 1.10 & 0.52 & 0.70 & 3.309 \end{bmatrix}$

Calculate the maximum eigenvalue (λ_{max}) = $\sum_1^n Wi/n$ = $\frac{3.05+2.879+3.309}{3}$ = 3.08167

Consistency index (CI) = $\frac{\lambda \max - n}{n-1}$ = 0.040835

Consistency Ratio = $\frac{CI}{RI}$ = $\frac{0.040835}{0.52}$ = 0.0785289 < 0.1

- Verify consistency of pairwise comparison matrix SSS_1 to SSS_{15} within respective goal.

$$\begin{bmatrix} SS1 & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1 \\ SSS2 & 1 & 1 & 2 \\ SSS3 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.006162 < 0.1

$$\begin{bmatrix} SS2 & SSS2 & SSS3 & SSS4 \\ SSS2 & 1 & 2 & 5 \\ SSS3 & 1/2 & 1 & 2 \\ SSS4 & 1/5 & 1/2 & 1 \end{bmatrix}$$

CI = 0.021846, CR = 0.0420114 <0.1

$$\begin{bmatrix} SS3 & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 1/9 & 1/9 \\ SSS5 & 9 & 1 & 0.5 \\ SSS6 & 9 & 2 & 1 \end{bmatrix}$$

CI = 0.009778, CR = 0.018803 <0.1

$$\begin{bmatrix} SS4 & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 6 & 1/4 \\ SSS8 & 1/6 & 1 & 1/9 \\ SSS9 & 4 & 9 & 1 \end{bmatrix}$$

CI = 0.011998, CR = 0.023074 < 0.1

$$\begin{bmatrix} SS5 & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1/9 & 1/2 \\ SSS9 & 9 & 1 & 9 \\ SSS10 & 2 & 1/9 & 1 \end{bmatrix}$$

CI = 0.019429, CR = 0.0373627 < 0.1

$$\begin{bmatrix} SS6 & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 9 & 6 \\ SSS10 & 1/9 & 1 & 1/2 \\ SSS11 & 1/6 & 2 & 1 \end{bmatrix}$$

CI = 0.038299, CR = 0.0736521 < 0.1

$$\begin{bmatrix} SS7 & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 1 & 1 \\ SSS13 & 1 & 1 & 2 \\ SSS14 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.0061623 < 0.1

$$\begin{bmatrix} SS8 & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 1/2 & 1 \\ SSS14 & 1 & 1 & 4 \\ SSS15 & 2 & 1/4 & 1 \end{bmatrix}$$

CI = 0.009311, CR = 0.0179056 < 0.1

$$\begin{bmatrix} SS9 & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 1 & 1/6 \\ SSS14 & 1 & 1 & 1/9 \\ SSS15 & 6 & 9 & 1 \end{bmatrix}$$ CI = 0.040767, CR = 0.0783987 < 0.1

- Verify consistency of pairwise comparison matrix SSS_1 to SSS_{15} within a goal of VF and PF.

$$\begin{bmatrix} VF & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1 \\ SSS2 & 1 & 1 & 2 \\ SSS3 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.006162 < 0.1

$$\begin{bmatrix} PF & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1/2 \\ SSS2 & 1 & 1 & 1 \\ SSS3 & 2 & 1 & 1 \end{bmatrix}$$

CI = 0.002856, CR = 0.0054923 < 0.1

$$\begin{bmatrix} VF & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 3 & 1 \\ SSS4 & 1/3 & 1 & 1 \\ SSS5 & 1 & 1 & 1 \end{bmatrix}$$

CI = 0.031853, CR = 0.0612563 < 0.1

$$\begin{bmatrix} PF & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 1 & 4 \\ SSS4 & 1 & 1 & 9 \\ SSS5 & 1/4 & 1/9 & 1 \end{bmatrix}$$

CI = 0.012576, CR = 0.0241842 < 0.1

$$\begin{bmatrix} VF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 1 & 1 \\ SSS5 & 1 & 1 & 2 \\ SSS6 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.006162 < 0.1

$$\begin{bmatrix} PF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 9 & 9 \\ SSS5 & 1/9 & 1 & 3 \\ SSS6 & 1/9 & 1/3 & 1 \end{bmatrix}$$

CI = 0.028973, CR = 0.0557205 < 0.1

$$\begin{bmatrix} VF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1 & 1 \\ SSS8 & 1 & 1 & 2 \\ SSS9 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.006162 < 0.1

$$\begin{bmatrix} PF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1/8 & 1/2 \\ SSS8 & 8 & 1 & 8 \\ SSS9 & 2 & 1/8 & 1 \end{bmatrix}$$

CI = 0.018742, CR = 0.036042 < 0.1

$$\begin{bmatrix} VF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1/4 & 1/4 \\ SSS9 & 4 & 1 & 2 \\ SSS10 & 4 & 1/2 & 1 \end{bmatrix}$$

CI = 0.011195, CR = 0.021528 < 0.1

$$\begin{bmatrix} PF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1 & 1/2 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 2 & 1 & 1 \end{bmatrix}$$

CI = 0.002856, CR = 0.0054492 < 0.1

$$\begin{bmatrix} VF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 1 & 1 & 2 \\ SSS11 & 1 & 1/2 & 1 \end{bmatrix}$$

CI = 0.003204, CR = 0.006162 < 0.1

$$\begin{bmatrix} PF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 1/2 & 1/4 \\ SSS10 & 2 & 1 & 1 \\ SSS11 & 4 & 1 & 1 \end{bmatrix}$$

CI = 0.006492, CR = 0.012485 < 0.1

$$\begin{bmatrix} VF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 9 & 8 \\ SSS13 & 1/9 & 1 & 3 \\ SSS14 & 1/8 & 1/3 & 1 \end{bmatrix}$$

CI = 0.045874, CR = 0.0882199 < 0.1

$$\begin{bmatrix} PF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 7 & 6 \\ SSS13 & 1/7 & 1 & 2 \\ SSS14 & 1/6 & 1/2 & 1 \end{bmatrix}$$

CI = 0.001955, CR = 0.0037605 < 0.1

$$\begin{bmatrix} VF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 3 & 1 \\ SSS14 & 1/3 & 1 & 1 \\ SSS15 & 1 & 1 & 1 \end{bmatrix}$$

$$\begin{bmatrix} PF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 2 & 6 \\ SSS14 & 1/2 & 1 & 9 \\ SSS15 & 1/6 & 1/9 & 1 \end{bmatrix}$$

CI = 0.031853, CR = 0.0612563 < 0.1

CI = 0.034809, CR = 0.0669397 < 0.1

- Verify consistency of pairwise comparison matrix SSS_1 to SSS_{15} within a goal of IM and TF

$$\begin{bmatrix} IM & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 1 & 1 \\ SSS2 & 1 & 1 & 2 \\ SSS3 & 1 & 1/2 & 1 \end{bmatrix}$$

CR = 0.006162 < 0.1

$$\begin{bmatrix} TF & SSS1 & SSS2 & SSS3 \\ SSS1 & 1 & 3 & 5 \\ SSS2 & 1 & 1 & 15 \\ SSS3 & 1/5 & 1/5 & 1 \end{bmatrix}$$

CR = 0.006135 < 0.1

$$\begin{bmatrix} IM & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 3 & 1/2 \\ SSS4 & 1/3 & 1 & 1/6 \\ SSS5 & 2 & 6 & 1 \end{bmatrix}$$

CR = 0.01 < 0.1

$$\begin{bmatrix} TF & SSS3 & SSS4 & SSS5 \\ SSS3 & 1 & 1 & 1/9 \\ SSS4 & 1 & 1 & 1/6 \\ SSS5 & 9 & 6 & 1 \end{bmatrix}$$

CR = 0.007 < 0.1

$$\begin{bmatrix} VF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 1 & 1 \\ SSS5 & 1 & 1 & 2 \\ SSS6 & 1 & 1/2 & 1 \end{bmatrix}$$

CR = 0.01 < 0.1

$$\begin{bmatrix} PF & SSS4 & SSS5 & SSS6 \\ SSS4 & 1 & 9 & 9 \\ SSS5 & 1/9 & 1 & 3 \\ SSS6 & 1/9 & 1/3 & 1 \end{bmatrix}$$

CR = 0.0072 < 0.1

$$\begin{bmatrix} VF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1/2 & 1/2 \\ SSS8 & 2 & 1 & 2 \\ SSS9 & 2 & 1/2 & 1 \end{bmatrix}$$

CR = 0.0150 < 0.1

$$\begin{bmatrix} PF & SSS7 & SSS8 & SSS9 \\ SSS7 & 1 & 1 & 1 \\ SSS8 & 1 & 1 & 2 \\ SSS9 & 1 & 1/2 & 1 \end{bmatrix}$$

CR = 0.00616 < 0.1

$$\begin{bmatrix} VF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1 & 1/4 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 4 & 1 & 1 \end{bmatrix}$$

CR = 0.022 < 0.1

$$\begin{bmatrix} PF & SSS8 & SSS9 & SSS10 \\ SSS8 & 1 & 1 & 1 \\ SSS9 & 1 & 1 & 5 \\ SSS10 & 1 & 1/5 & 1 \end{bmatrix}$$

CR = 0.023 < 0.1

$$\begin{bmatrix} VF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 1 & 1 \\ SSS10 & 1 & 1 & 5 \\ SSS11 & 1 & 1/5 & 1 \end{bmatrix}$$

CR = 0.022 < 0.1

$$\begin{bmatrix} PF & SSS9 & SSS10 & SSS11 \\ SSS9 & 1 & 5 & 7 \\ SSS10 & 1/5 & 1 & 7 \\ SSS11 & 1/7 & 1/7 & 1 \end{bmatrix}$$

CR = 0.0104 < 0.1

$$\begin{bmatrix} VF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 1/3 & 1/3 \\ SSS13 & 3 & 1 & 2 \\ SSS14 & 3 & 2 & 1 \end{bmatrix}$$

CR = 0.01002 < 0.1

$$\begin{bmatrix} PF & SSS12 & SSS13 & SSS14 \\ SSS12 & 1 & 1/8 & 1/2 \\ SSS13 & 8 & 1 & 8 \\ SSS14 & 2 & 1/8 & 1 \end{bmatrix}$$

CR = 0.036 < 0.1

$$\begin{bmatrix} VF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 1/8 & 5 \\ SSS14 & 8 & 1 & 1/2 \\ SSS15 & 1/5 & 2 & 1 \end{bmatrix}$$

CR = 0.031 < 0.1

$$\begin{bmatrix} PF & SSS13 & SSS14 & SSS15 \\ SSS13 & 1 & 1/2 & 8 \\ SSS14 & 2 & 1 & 5 \\ SSS15 & 1/8 & 1/5 & 1 \end{bmatrix}$$

CR = 0.0378 < 0.1

Since AHP was consistent, the MCDM model for the study was AHP Hierarchy and used for result analysis in the entire aforementioned consistency ratio tests. Without result analysis, consistency verification was merely a numerical value and of no use. However, because the current investigation's objective might take into account the consistency test of the two ways of production for result analysis and discussion, it has been very difficult and time consuming to analyze the full set of results.

3.5 Proposed Framework

The study proposed a framework for the assessment purpose of manufacturing methods presented in Fig 3.11 below. The proposed framework divided into four phases with seven sections. The description of each phase and section has presented in Table 3.17 below.

In the previous studies, authors have identified many frameworks for performance assessment purpose but no one can put a complete framework for perfect decision purpose. Some authors try to include infinite factors for performance indicators selection purpose and it leads to a complex unsolved system, case for incommensurable and conflict with each other in the decision analysis. Due to this and other related case inspired to propose the modified framework to minimize decision complexity.

Table 3.17: Description of proposed framework

Phase One The primary opinion of this phase was the manufacturer keeps considering sustainable manufacturing operations in the three pillars i.e., economic, environmental and social. Literature shows that yet different authors use one or two sometimes use three pillars but their weighing were not equal. Most of them focus on related to profit, which directly link to economic factor but in the framework the three criteria of sustainability must judge equally for getting a sustainable product.
Phase Two In the second phase main thing performed were the indicator selection case. Of course, different authors try to identify indicators under the umbrella of three aspects of sustainability i.e., economic, social and environmental with a consideration of complex factors. However, in this proposed framework the factors for indicator selection purpose were categorize in to a generalized six basic factors, which were under a consideration of social life impact, manufacturing environment with product type, economic value generation via technology assessment, manufacturing strategy, government policy, and factors for the issue of sustainability. Meanwhile, after the selection of indicators by consideration of all factors completed, indicator prioritization to the case must be perform by a statistical frequency counting method, it was very important for give priority and select the perfect indicators to the case.
Phase Three In the third phase of the framework, data collection can do with the help of questionnaire surveys and interviews. This data can be analyzed with the MCDM techniques i.e., AHP, ANP, TOPSIS, or any other hybrid approach. Other models such as miscellanies, utility based, and ranking can used for the data analysis. By using analyzed data can determine the sustainability performance using level-by-level fitting of contributions.
Phase four Social well-being, environmental friendliness and economic benefits were discuses from three aspects of sustainability.

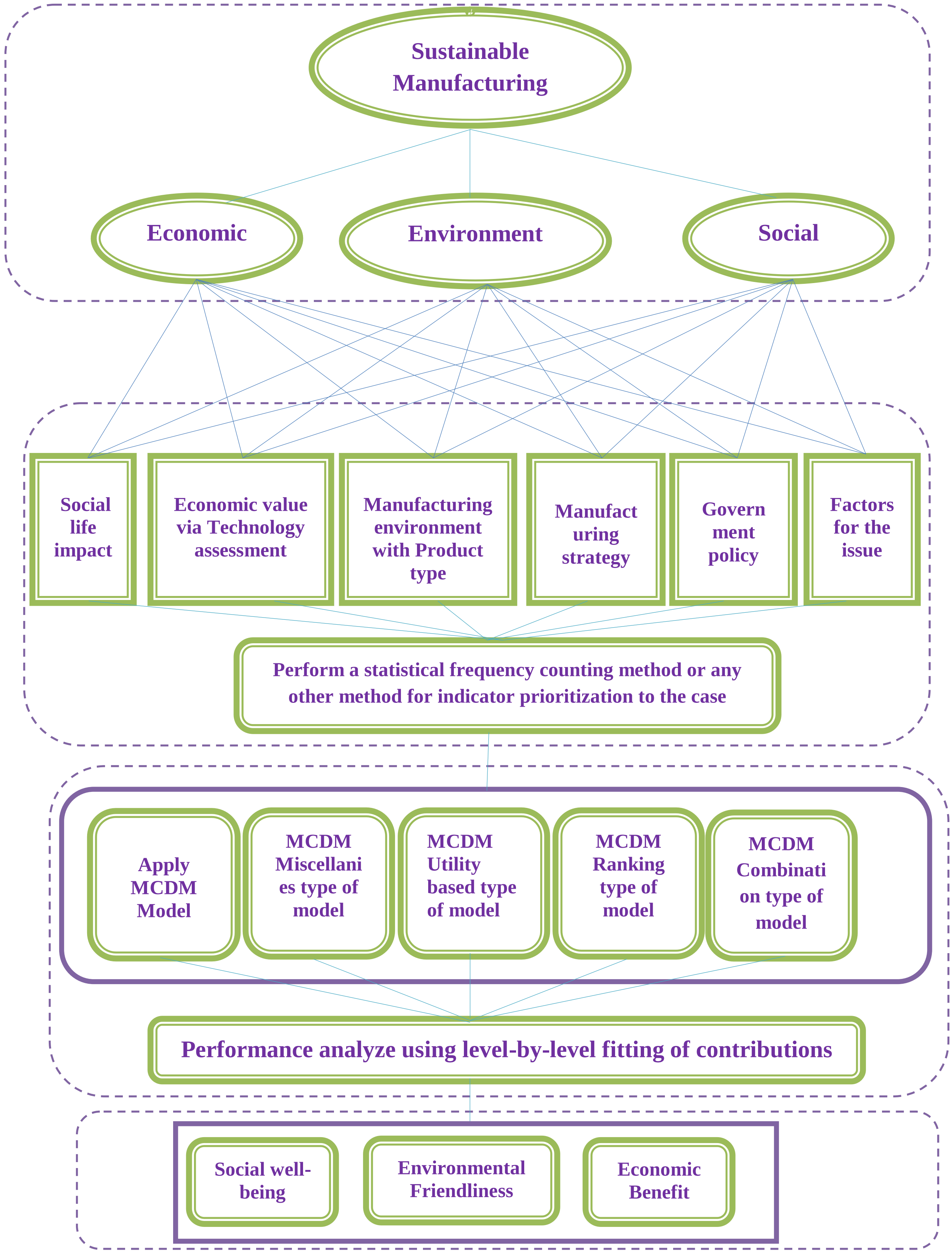


Fig 3.11: Framework

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussions regarding the sustainability performance assessment of the two methods used to manufacture plastic cups: vacuum forming and pressure forming. The sustainability performance assessment was conducted through the three pillars—economic, environmental, and social—along with their corresponding alternative indicators. After properly selecting the appropriate indicators for each of the three pillars, a decision tree was established to break down the problem into different levels, simplifying the analysis of each judgment matrix and the calculation of alternatives. A pairwise comparison judgment table was created after consulting with two experts for their assessments. For each judgment, consistency verification was carried out by determining the consistency ratios for each judgment matrix. The next section will discuss the assessment results for the three pillars.

4.2 Economic Assessment

For the overall economic performance assessment purpose, indicators located in Table 4.1 below have selected based on their contribution the objective of the research with in its specific pillar.

Table 4.1: Selected indicators for economic performance assessment

S_1	SS_1	SS_2	SS_3
SSS-1	SSS_1	SSS_3	SSS_4
SSS-2	SSS_2	SSS_4	SSS_5
SSS-3	SSS_3	SSS_5	SSS_6

From the hierarchy of indicators, the first assessment in the economic pillar has held by the manufacturing cost. Based on the assessment value from Graph 4.1, the manufacturing cost assessment vacuum forming method score (0.028959) the first, which shows better performance, and the largest contribution comes from actual machining cost (sss_2). Indeed, the actual machining cost of vacuum forming was cheaper than pressure forming. Whereas the score of pressure forming were 0.005492, with its contribution comes from actual machining cost and production cost.

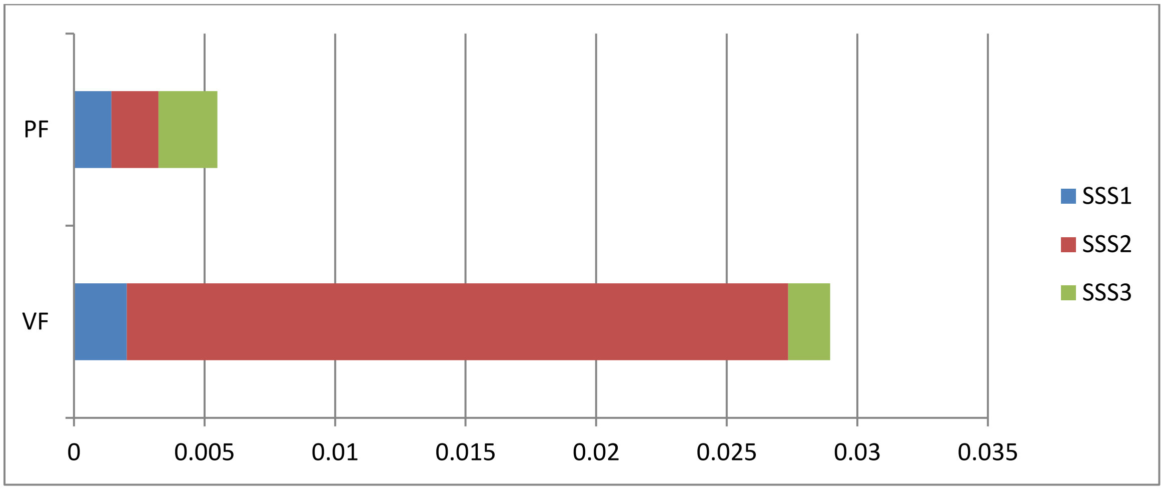


Fig 4.1: Performance graph of manufacturing cost in VF (vacuum forming) and PF (pressure forming)

For further result analysis and suppose to digest in detail the score of each indicator, Table 4.2 below show that the score of each indicator either in percentage or individual score with respect to the performance assessment under the economic pillar through manufacturing cost of the two manufacturing method.

Table 4.2: Manufacturing cost performance assessment of two methods.

Total Score	0.028959		0.005492	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_1	6.97%	0.00202	26.11%	0.001434
SSS_2	87.46%	0.02533	32.77%	0.0018
SSS_3	5.56%	0.001609	41.11%	0.002258
	VF		PF	
Manufacturing cost				

The next important indicators under economic pillar from the hierarchy were the machining performance. Like the manufacturing cost, the assessment of machining performance has held by using the selected indicators in Table 4.1. Vacuum forming (0.061256), shows better performance under the assessment of machining performance than pressure forming (0.024185). The result of performance assessment graph has clearly observed in Fig 4.2 below.

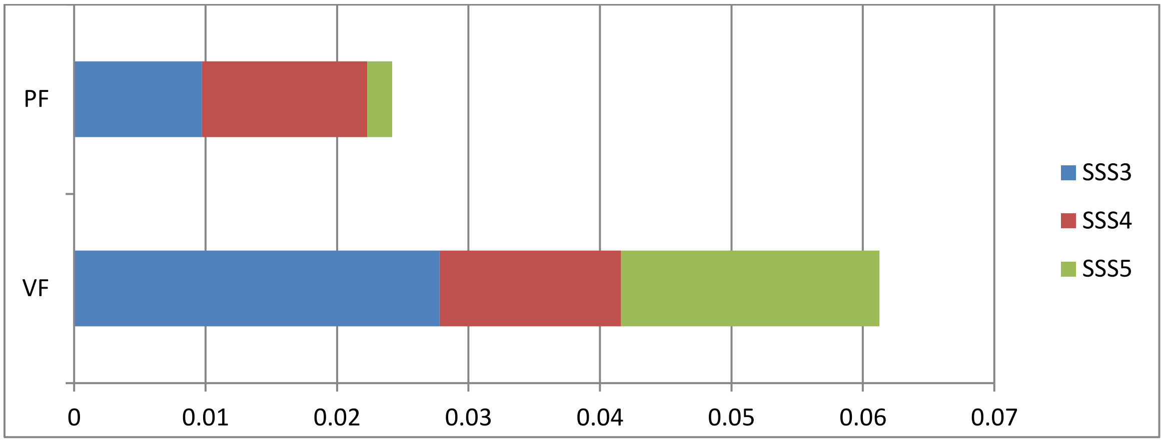


Fig 4.2: Performance assessment graph of machining performance in the two methods

For more clarification and know about the contribution of each indicator, Table 4.3 shows detail scores of each indicator. In order to show more clearly and helps to identify the major contributor, the result was observed in percentage and individual score. The percentage result was done with in its respective score while the individual score gets from the overall assessment of machining performance under the economic pillar of the two manufacturing method.

Table 4.3: Machining performance assessment of two methods

Total Score	0.061256		0.024185	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_3	45.39%	0.027808	40.13%	0.009705
SSS_4	22.54%	0.013807	52.03%	0.012584
SSS_5	32.06%	0.019641	7.84%	0.001896
	VF		PF	
	Machining Performance			

The next and last indicator for economic hierarchy was production efficiency. Pressure forming (0.05572) perform better vacuum forming (0.006162) with major contribution comes from production rate. The major contribution in pressure forming comes from sss_4 because material distribution was better in pressure forming. The performance assessment result of each indicator with in its contributor for the assessment of production efficiency was observe in Fig 4.3 below.

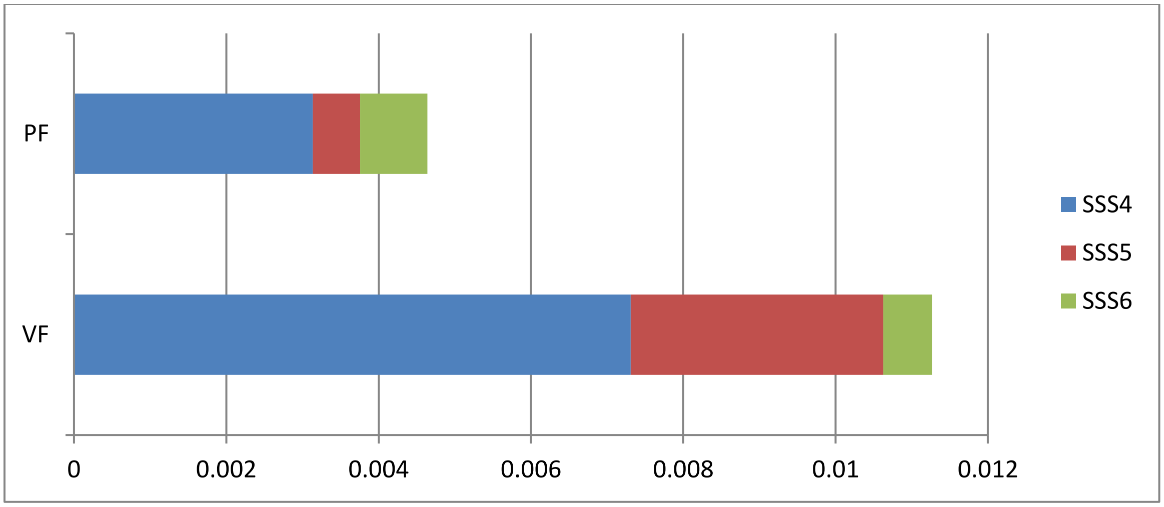


Fig 4.3: Performance assessment graph of production efficiency in the two methods

The graphical representation of any result analysis was difficult to know the specific value of each parameter. Especially in the current case the contribution of each indicator was very necessary to give justification for the performance of the manufacturing method. So, in addition to the above graphical result analysis, Table 4.4 below give detail information about the performance assessment of production efficiency in the economic pillar by percentage and individual score.

Table 4.4: Production performance assessment of two methods

Total Score	0.006162		0.05572	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_4	32.78%	0.00202	79.38%	0.044232
SSS_5	41.10%	0.002533	13.95%	0.007772
SSS_6	26.11%	0.001609	6.67%	0.003716
	VF		PF	
	Production Efficiency			

4.3 Environment Assessment

By considering, the contribution of environmental pillar to sustainability assessment and plan to get better performance result and within under the consideration of the study objective, set all Table 4.5 indicators for the purpose of environmental performance assessment.

Table 4.5: Selected indicators for environmental performance assessment

S_2	SS_4	SS_5	SS_6
SSS-1	SSS_7	SSS_8	SSS_9
SSS-2	SSS_8	SSS_9	SSS_{10}
SSS-3	SSS_9	SSS_{10}	SSS_{11}

The first environmental indicator from the hierarchy was energy consumption. Pressure forming (0.036041) method of manufacturing has been perform better than vacuum forming (0.006162) because the amount of energy consumption by the machine was 150kw which was very high than vacuum forming with in its major contribution comes from sss_7, energy consumption by the machine. The assessment results were clearly observed in Fig 4.4 below.

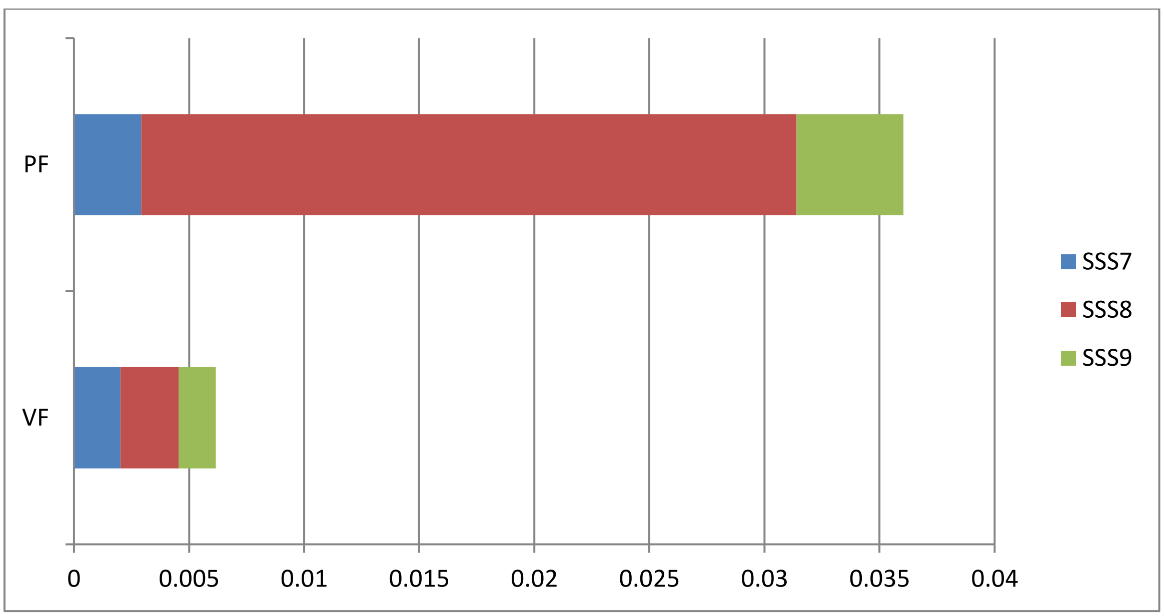


Fig 4.4: Performance assessment graph of energy consumption in the two methods

In addition to the above fig 4.4 graphical performance result analysis, Table 4.6 below show a detail score of each indicator contribution and also seen the percentage result of each with in its corresponding total score. In both cases more than half contribution comes from energy consumption by the machine, it has been the great impact for the manufacturing of any product.

Table 4.6: Energy consumption performance assessment of two methods

Total Score	0.006162		0.036041	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_7	32.78%	0.00202	8.11%	0.002926
SSS_8	41.10%	0.002533	93.60%	0.028465
SSS_9	26.11%	0.001609	12.90%	0.00465
VF			PF	
Energy Consumption				

After finish energy consumption performance assessment, the hierarchy leads to assess the type of material. Under type of material assessment vacuum forming (0.021528), perform better than pressure forming (0.005492). The major contribution comes from sss_9. The assessment of raw material includes weight of the product and waste per part, it was high in pressure forming method. Fig 4.5 below show graphical performance assessment analysis of type of material of the two methods

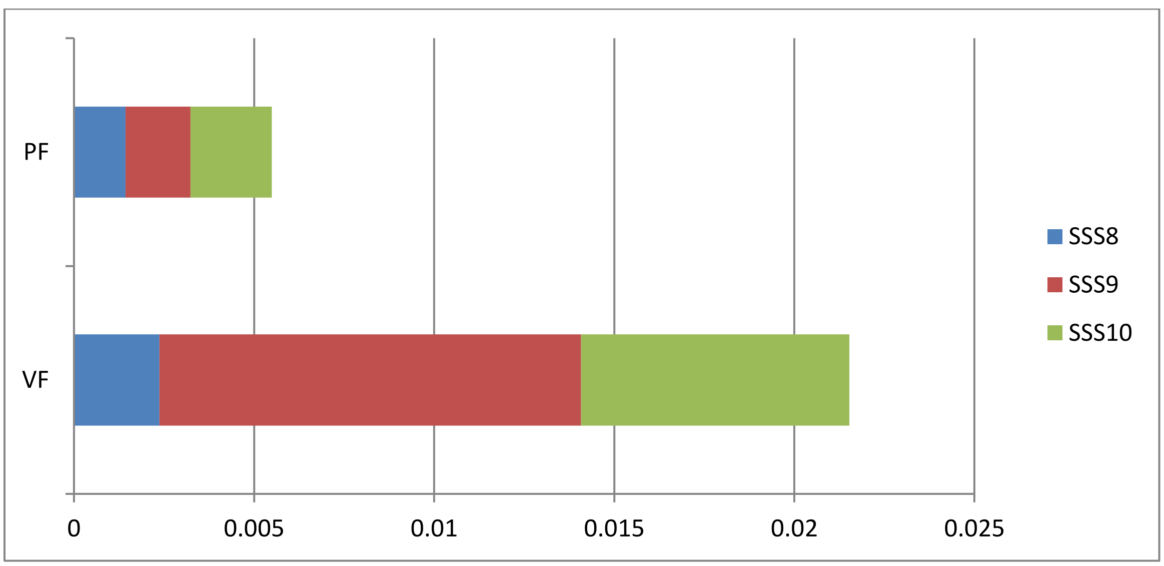


Fig 4.5: Performance assessment graph of type of material in the two methods

The above fig 4.5 graphical result analysis of performance of material does not show the individual score instead it was very better to know the percentage contribution of each indicator to the respective goal. Due to this the next table 4.7 clearly show that the contribution of each indicator in percentage and individual score.

Table 4.7: Type of material performance assessment of two methods

Total score	0.021528		0.005492	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_8	11.03%	0.002374	26.11%	0.001434
SSS_9	54.37%	0.011706	32.77%	0.0018
SSS_{10}	34.59%	0. 007448	41.11%	0.002258
VF			PF	
Type of Material				

From the hierarchy the last indicator for environmental assessment was waste and pollution. Pressure forming (0.012485) performs better than vacuum forming (0.006162). Better performances appear in pressure forming due to the establishment of waste management mechanism in its system. The result of the assessment was graphically represented in fig 4.6 below.

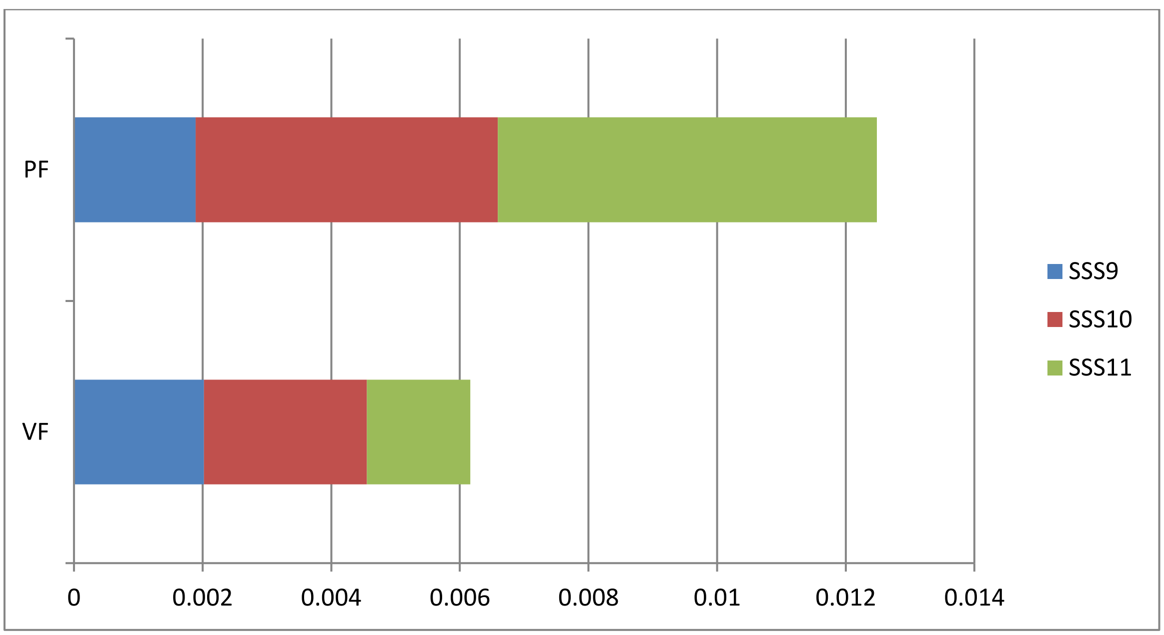


Fig 4.6: Performance assessment graph of waste and pollution in the two methods

In addition to graphical result analysis, table 4.8 below show detail score of each indicator value with respect to the corresponding score.

Table 4.8: Waste and pollution performance assessment of two methods

Total score	0.006162		0.012485	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_9	32.78%	0.00202	15.13%	0.001889
SSS_{10}	41.10%	0.002533	37.66%	0.004703
SSS_{11}	26.11%	0. 001609	47.20%	0.005893
VF			PF	
Waste and Pollution				

4.4 Social Assessment

Based on the objective of the research, for the overall social performance assessment purpose, indicators located in Table 4.9 below have selected by considering the contribution of social pillar to sustainability assessment and plan to get better performance result.

Table 4.9: Selected indicators for social performance assessment

S_3	**SS_7**	**SS_8**	**SS_9**
SSS-1	SSS_{12}	SSS_{13}	SSS_{13}
SSS-2	SSS_{13}	SSS_{14}	SSS_{14}
SSS-3	SSS_{14}	SSS_{15}	SSS_{15}

The first influential indicator from the hierarchy was health issue. Vacuum forming (0.08822) method perform better than pressure forming (0.003761). The great contribution for vacuum forming comes from workers health, it includes risk minimization for worker and the method by itself was safe for workers than pressure working. Fig 4.7 below show a detail graphical representation of the performance assessment of health issue in the two manufacturing method.

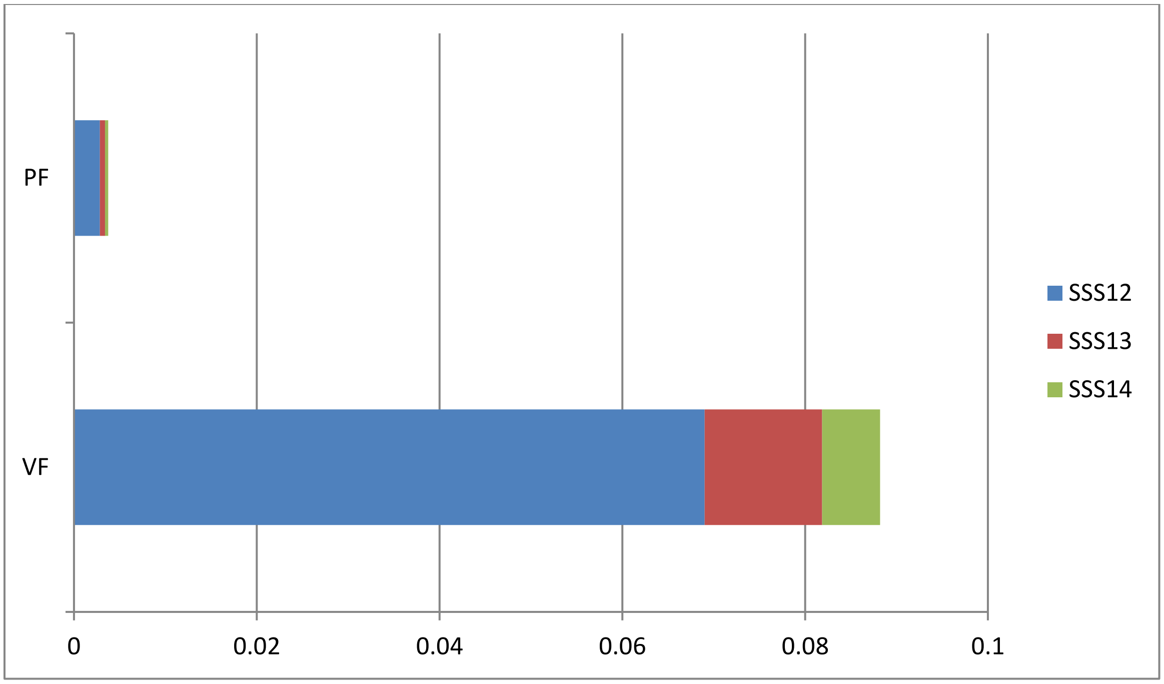


Fig 4.7: Performance assessment graph of health issue in the two methods

For further analysis and know the contribution of each indicator, Table 4.10 below show percentage and individual score of each indicator with in its respective goal of health issue.

Table 4.10: Health issue performance assessment of two methods

Total Score	0.08822		0.00376	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_{12}	78.22%	0.069006	75.13%	0.002825
SSS_{13}	14.55%	0.012841	14.96%	0.000563
SSS_{14}	7.22%	0.006373	9.90%	0.000373
	VF		PF	
Health Issue				

The second important indicator from the hierarchy under the social scheme was the safety issue. Pressure forming (0.06694) performs better due to all the near miss and worker safety would be improve by technician and operator trainings. Fig 4.8 below show graphical representation of performance assessment of safety issue in the two methods of manufacturing

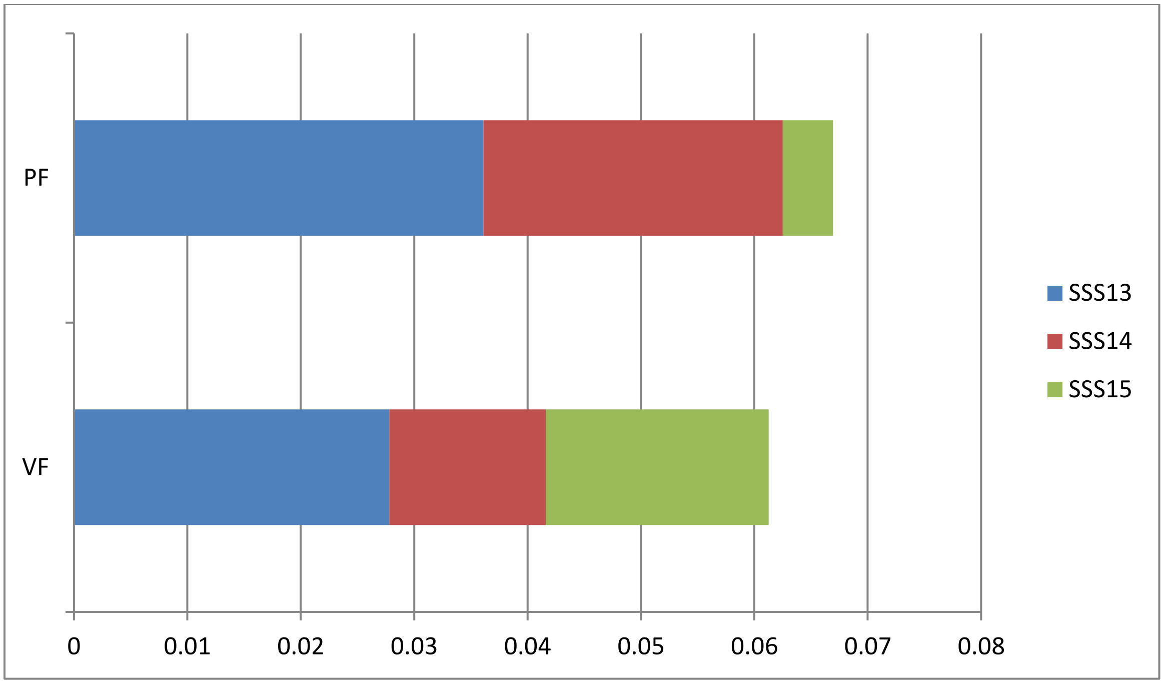


Fig 4.8: Performance assessment graph of safety issue in the two methods

For more digestion of the result and grasp a clear concept about the individual performance of indicators, Table 4.11 below shows detail information about percentage coverage and individual score of each indicator for social pillar through safety issue.

Table 4.11: Safety issue performance assessment of two methods

Total Score	0.061256		0.06694	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_{13}	44.2857%	0.027808	61.502%	0.0361
SSS_{14}	38.7302%	0.013807	29.2358%	0.026417
SSS_{15}	16.9841%	0.019641	9.2622%	0.004423
	VF		PF	
Safety Issue				

The last social indicator from the hierarchy was the workforce issue. Vacuum forming (0.061256) method perform better than pressure forming method (0.034265), the large contribution for vacuum forming comes from worker safety. The graphical result analysis was detail observed in fig 4.9 below.

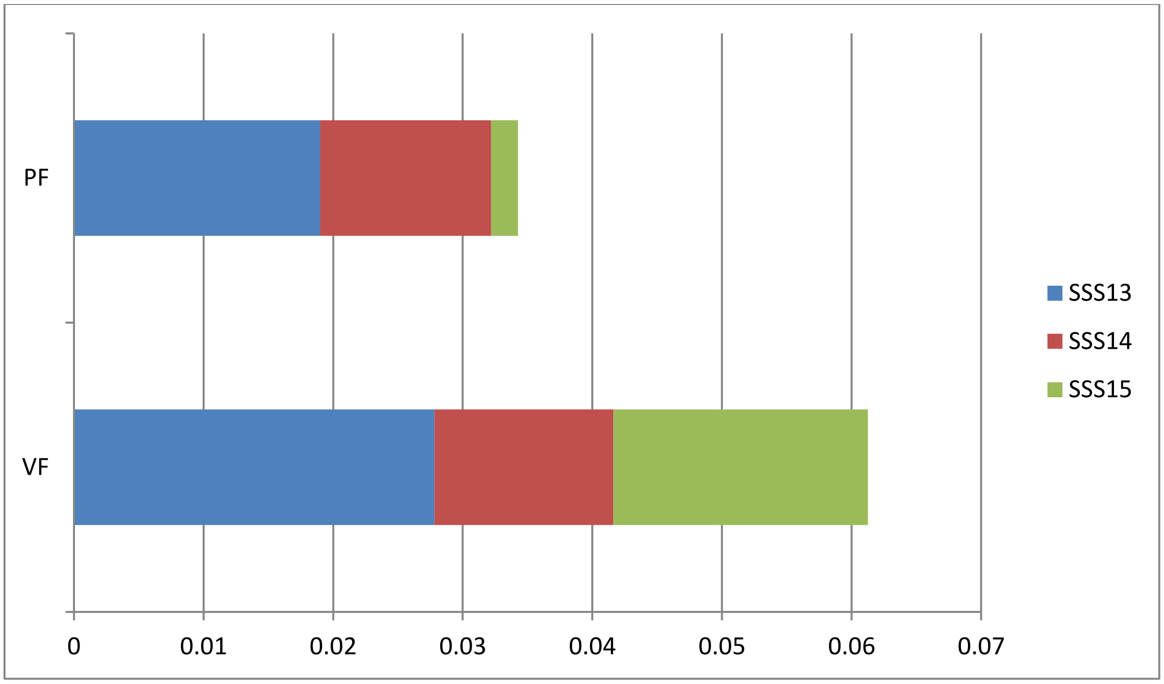


Fig 4.9: Performance assessment graph of workforce issue in the two methods

The percentage coverage and individual score of each indicator to the social pillar through workforce issue was indicate in Table 4.12 below. It was very important for the manufacturer to know the contribution of each indicator in either percentage or individual score.

Table 4.12: Workforce issue performance assessment of two methods

Total Score	0.061256		0.034265558	
	Percentage (%)	Individual score	Percentage (%)	Individual score
SSS_{13}	45.39%	0.027808	55.44%	0.018998
SSS_{14}	22.53%	0.013807	38.51%	0.013194
SSS_{15}	32.06%	0.019641	7.33 1.97%	0.002073
VF			PF	
Workforce Issue				

4.5 Overall Sustainability Assessment

To analyses overall sustainability performance, the three pillars of economic, social, and environmental performance have typically used. The selected indicators to their respective pillars were list in Table 4.13 below.

Table 4.13: Selected indicators for overall sustainability performance assessment

S	S_1	S_2	S_3
SS-1	SS_1	SS_4	SS_7
SS-2	SS_2	SS_5	SS_8
SS-3	SS_3	SS_6	SS_9

By using selected indicator and sum up the whole result analyzed with respect to corresponding pillar can be know the performance assessment result of sustainability in the three perspectives. Fig 4.10, below show performance assessment graph of sustainability in the three schemes, under the economic scheme both of the method almost has equal performance, with having a little more performance observed in vacuum forming which it come from the cost of the manufacturing difference and also the difference in actual machining cost for large scale production. Meanwhile under the environmental scheme, the pressure forming method performs better than vacuum forming its major contribution comes from energy consumption by the machine. Likewise, in the social scheme vacuum forming perform better than the pressure forming due to all the social issue in vacuum forming method has minimized by training and education of technicians and operators.

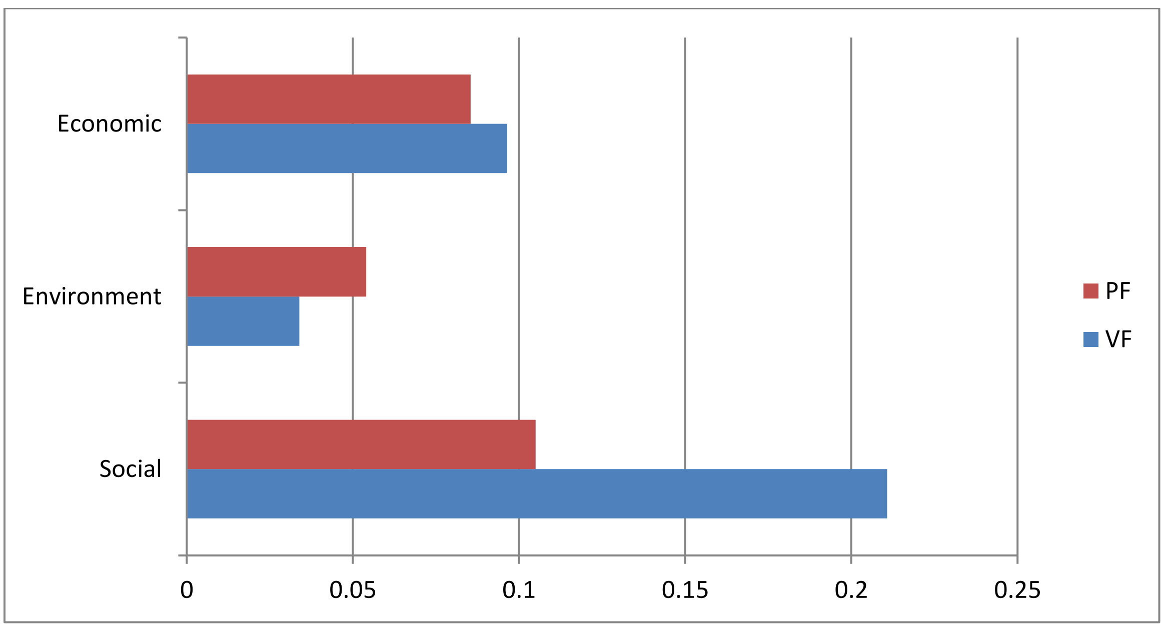


Fig 4.10: Performance assessment graph of sustainability in the three schemes

The contribution of each indicator to the respective pillar were analyses in above graph 4.10 and additionally in detail the score of each individual value were observed from Table 4.14 to Table 4.16 below.

Table 4.14: Economic performance assessment result of two methods

Total Score	0.096377		0.085397	
SS_1	30.04%	0.028959	6.43%	0.005492
SS_2	63.55%	0.061256	28.32%	0.024185
SS_3	6.39%	0.006162	65.24%	0.05572
VF			PF	
Economic				

Table 4.15: Environmental performance assessment result of two methods

Total Score	0.0338552		0.054021	
SS_4	18.20%	0.006162	66.71%	0.036041
SS_5	63.58%	0.021528	10.16%	0.005492
SS_6	18.20%	0.006162	23.11%	0.012485
VF			PF	
Environment				

Table 4.16: Social performance assessment result of two methods

Total Score	0.210732		0.10496	
SS_7	41.86%	0.08822	3.58%	0.003761
SS_8	29.06%	0.061256	63.77%	0.06694
SS_9	29.06%	0.061256	32.61%	0.03423
VF			PF	
Social				

The next and last assessment held the overall sustainability assessment. There were two manufacturing methods (candidates) and have very closest assessment values under three pillars, so in order to differentiate the best manufacturing method, it needs to apply a collective scoring and ranking methods for decision making analysis purpose.

From the collective scoring and ranking method for decision making analysis purpose, Borda count method were an excellent way to take full consideration of the candidate's preference and give individual score for candidates than the other [70]. The primary work of the method was to rank the candidate of the two manufacturing method under the three schemes. Table 4.17, below show the ranking of the option of the two manufacturing method through the three candidates.

Table 4.17 Ranking of manufacturing methods

Number of options	Economic	Environmental	Social
	18.177	8.787	31.57
Vacuum forming	1	2	1
Pressure forming	2	1	2

After properly ranked the candidates or options, then calculate the Borda score (Sum) value by using equation 4.1.

Borda score = (Total No of candidate – Rank of a given candidate) * Multiplier ……. eqn 4.1[70]

By using the above formula, the score of each candidate or option were calculated and filled in Table 4.18 below.

Table 4.18: Borda count score (sum) value

Multiplier	18.177	8.787	31.57	Borda score (Sum)
VF	(2-1) *18.2=18.17	(2-2) * 8.787=0	(2-1) * 31.57=39.57	49.75
PF	(2-2) *18.17=0	(2-1) * 8.787=8.787	(2-2) * 31.57=0	8.787

In addition to the above score calculation, it was also analyzed the percentage coverage of each candidate as follows:

- Total Borda count sum= 18.177+8.787+31.57 = 58.54

Percentage Borda count sum of each candidate were:

- $VF = \frac{9.64}{58.54} * 100\% + \frac{3.38}{58.54} * 100\% + \frac{21.07}{58.54} * 100\% = 58.23\%$
- $PF = \frac{8.53}{58.54} * 100\% + \frac{5.40}{58.54} * 100\% + \frac{18.50}{58.54} * 100\% = 41.74\%$

The graphical representation of result analysis of the Borda count score (sum) and percentage Borda count can observe in Fig 4.11 below.

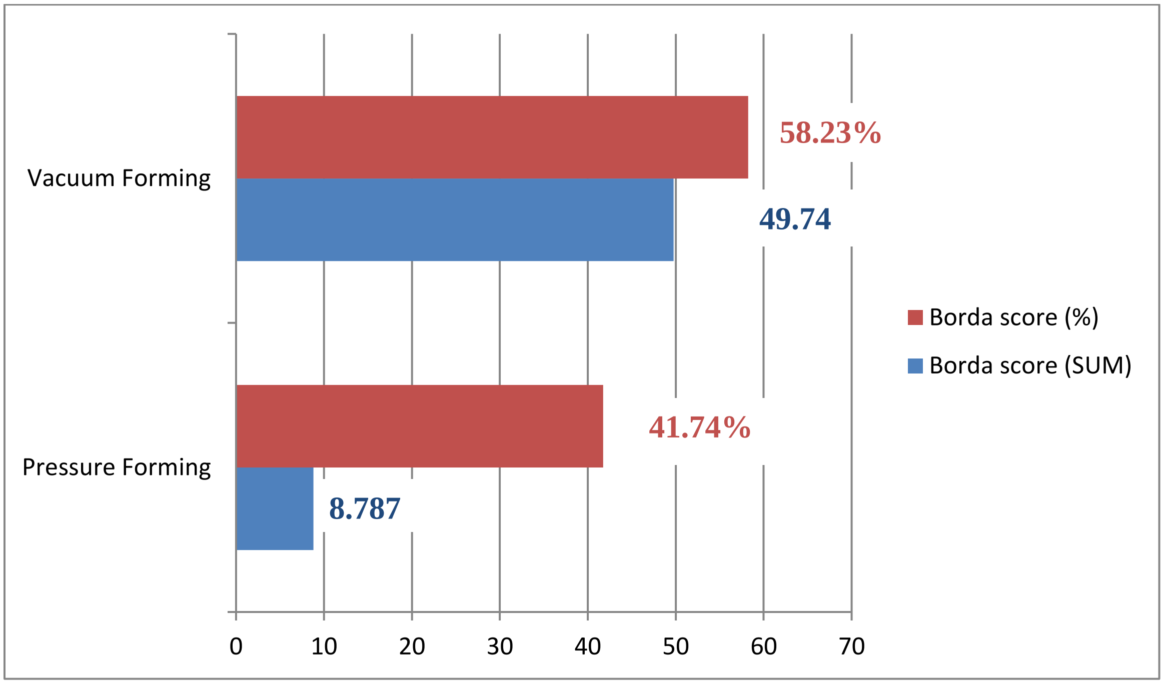


Fig 4.11: overall sustainability performance assessment

From the Borda count analysis can observed that the vacuum forming method becomes the first ranking under the overall sustainability assessment. Based on the outcome of the study therefore recommends that the company begin producing cups using the vacuum forming method in order to achieve overall sustainability and aid to minimize the problems that the company faced.

4.6 Technical assessment result of the manufacturing methods

By using the selected indicators and sum up the whole result analyzed with respect to corresponding pillar can be know the performance assessment result of sustainability in the three perspectives. Table 4.19, below show performance assessment result of sustainability in the three schemes, under the economic scheme both of the method almost has equal performance, with having a little more performance observed in injection molding. Meanwhile under the environmental scheme, the thermoforming methods performs better than injection molding. Likewise, in the social scheme injection molding perform better than the thermoforming.

Table 4.19: Total score of the two manufacturing method

Total Score	0.096377		0.085397	
S_1	51.66%	0.5166	49.86%	0.4986
S_2	47.00%	0.4700	56.00%	0.5600
S_3	58.00%	0.5800	34.00%	0.3400
IM			TF	
Sustainability				

Total score analysis by applying borda count method is as follows in Table 4.20 below:

Table 4.20 Ranking of manufacturing methods

Number of options	Economic	Environmental	Social
	10.15	10.3	9.19
IM	1	2	1
TF	2	1	2

After properly ranked the candidates or options, then calculate the Borda score (Sum) value by using equation 4.1.

Borda score = (Total No of candidate – Rank of a given candidate) * Multiplier …….eqn 4.1[70]

By using the above formula, the score of each candidate or option were calculated and filled in Table 4.21 below.

Table 4.21: Borda count score (sum) value

Multiplier	10.15	10.3	9.19	Borda score (Sum)
VF	(2-1) *10.2	(2-2) * 10.3=0	(2-1) * 9.19	19.35
PF	(2-2) *10.2=0	(2-1) * 10.3	(2-2) * 9.19=0	10.3

In addition to the above score calculation, it was also analyzed the percentage coverage of each candidate as follows:

- Total Borda count sum = 29.65

Percentage Borda count sum of each candidate were:

- $VF = \frac{5.166}{29.65} * 100\% + \frac{4.70}{29.65} * 100\% + \frac{5.80}{29.65} * 100\% = 52.83\%$
- $PF = \frac{4.9}{29.65} * 100\% + \frac{5.6}{29.65} * 100\% + \frac{3.4}{29.65} * 100\% = 46.88\%$

From the Borda count analysis can observed that the injection molding (IM) method becomes the first ranking under the overall sustainability assessment than thermoforming method (TF).

To visually represent the assessment values of the three manufacturing methods (Injection Molding, Vacuum Forming, and Pressure Forming) under the selected parameters—Economic, Environmental, and Social here can create a graphical representation in fig 4.12 below, as it allows a clear comparison of multiple dimensions for different items.

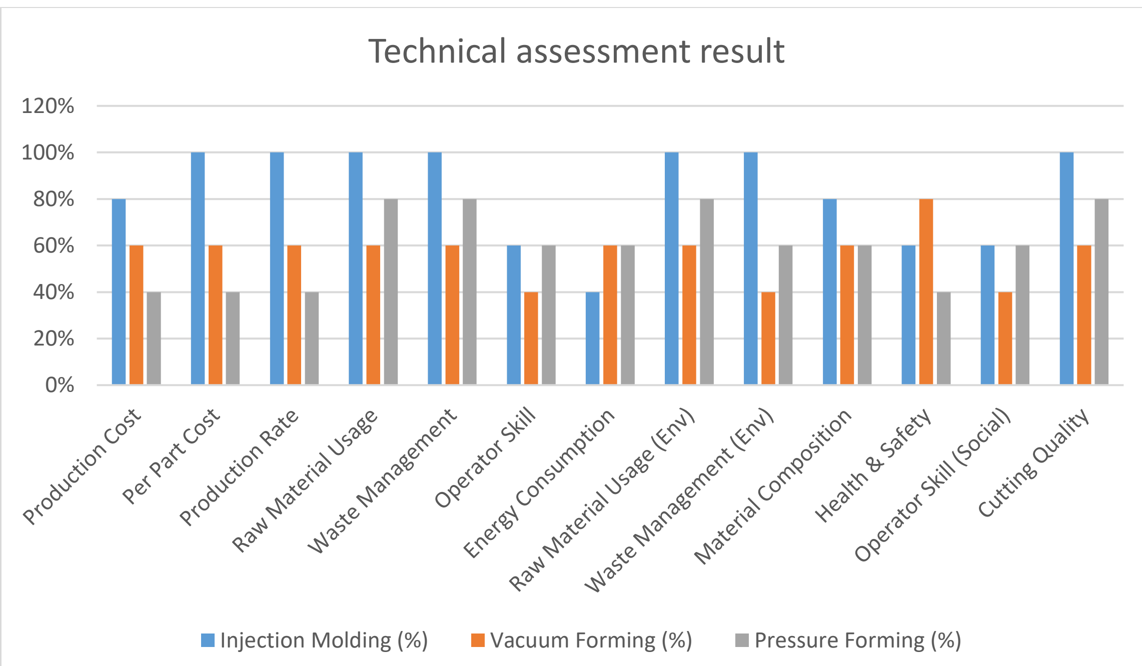


Fig 4.12: Technical assessment result of the three manufacturing methods

4.7 Validations of the Model

The validation of the model developed for assessing sustainability performance of the plastic cup manufacturing process using the Analytic Hierarchy Process (AHP) involves ensuring that the methodology is both accurate and reliable in the contexts of sustainability. Below are the formulations of the appropriate techniques for the proof of the validation of the model.

1. Statistical Validation Techniques (i.e, Consistency Index in AHP)

In AHP, the pairwise comparison matrices used to establish the relative importance of criteria need to be consistent. The models validation process should assess the consistency of these matrices. This is typically done through the Consistency Ratio (CR):

$$CR = \frac{\lambda max - n}{(n-1)}$$

Where:

- λmax is the maximum eigenvalue of the pairwise comparison value
- n is the number of criteria being compared

A *CR* value of less than 0.1 ($0<CR<0.1$) is generally considered acceptable for consistency in AHP. Based on this general truth the whole pair wise comparison matrices generated in the AHP model passes the consistency limit and prove one of the requirements of validity (Consistency check in section 3.4.5).

2. Comparison with Established Models

In comparing the sustainability assessment values of injection molding, vacuum forming, and pressure forming across different plastic product cases using two distinct AHP models [76, 77], notable differences were observed in the environmental, economic, and social dimensions. However, in both models, the sustainability performance values consistently ranked highest for injection molding, followed by vacuum forming, with pressure forming ranking last. This consistent outcome across the models highlights that injection molding excels primarily in economic efficiency, while vacuum forming performs better in environmental sustainability. Pressure forming tends to score lower in both models, likely due to its higher energy consumption and material waste generation during production [76, 77]. Consequently, this study model delivers the same output, proving its validity.

CHAPTER FIVE

5. CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1. Conclusions

In this thesis, the multi-criteria decision-making methodology was effectively applied to examine the sustainability performance of different cup manufacturing methods. The three pillars—economic, environmental, and social—along with the corresponding alternative indicators, were used to measure sustainability performance.

By employing the Analytic Hierarchy Process (AHP) technique as a decision-making tool, the sustainability performance of the two plastic cup manufacturing methods, vacuum forming and pressure forming, was thoroughly investigated. The findings indicate that vacuum forming demonstrates better overall sustainability performance. The total sum approach scores for vacuum forming were 49.75, while pressure forming scored 8.787. Based on the percentage Borda count method, vacuum forming scored 58.23%, and pressure forming scored 41.74%.

The sustainability performance of each alternative was assessed, including the contributions of each indicator. In the environmental dimension, pressure forming showed better performance with a score of 0.054021, where the largest contribution came from energy consumption (score = 0.036041). In the economic and social dimensions, vacuum forming scored 0.096377 (9.6377%) and 0.2107 (21.07%), respectively. The largest contribution to the economic dimension came from machining performance (score = 0.0613), while the largest contribution to the social dimension came from health issues (score = 0.088).

Additionally, the model was used to assess the sustainability performance of injection molding and thermoforming methods, which scored 52.83% and 46.88%, respectively.

The outcomes of this thesis analysis are significant, as they provide insights into how similar products manufactured using different production processes—such as the two methods analyzed in this thesis—perform in terms of sustainability. The research also includes a framework that yields accurate assessment results.

5.2. Recommendation

Based on the result of the thesis, it would be doable to recommend that plastic cup manufacturers concentrate on producing cups using vacuum forming in order to boost overall performance and make problems more straightforward to solve.

5.3. Future Work

From the perspective of the present study, the author recommends that future research consider the following avenues:

- ✓ Conduct an analysis of the outcomes at each level of the decision hierarchy, compare these results with the overall summative outcomes, and, based on these comparisons, critically evaluate the contributions of the three sustainability pillars.
- ✓ Due to the lack of comprehensive product distribution data, it was not feasible to incorporate a market assessment in the current study. Future research should consider integrating a market assessment to further assess the product's sustainability performance in a real-world context.

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APPENDICES

Appendix I

AAiT

Addis Ababa Institute of Technology

Addis Ababa University

School of Mechanical and Industrial Engineering

Tel +251 (0)111 232414

Date: 26/06/2023

DATA COLLECTION REQUEST FORM

To:- BA Manufacturing Plc

Mr/Mrs. Abebaw Mengistu, is a BSc/MSc/PhD student in our School at, Addis Ababa Institute of Technology, Addis Ababa University at this Moment he/she is doing his/her thesis/ Project/ term paper entitled

"Multi-criteria Decision Making Methodology for Sustainability Performance of Plastic Cup Manufacturing by Using AHP

In order to successfully complete his/her paper, the student wants to be allowed to do experimental research in your factory/Industry /Organization since the experimental equipment needed for the research is not found in the Institute.

The School strongly appreciates for any sort of assistance you provide to our student related to his/her thesis/ Project/ term paper. In addition, we would like to inform you that the data is required for educational purpose.

Thank you in advance for your cooperation.

Dr Araya Abera

Dean, School of Mechanical and Industrial Engineering

Addis Ababa Institute of Technology

Addis Ababa University

Addis Ababa Institute of Technology | King George VI Street | Addis Ababa | Ethiopia | P.O.Box 385

BA MANUFACTURING PLC

Date: 29/06/2023

Verification Letter

According to the letter from the AAU student dated June 26, 2023, requesting information from our company in order to prepare his thesis and use as a data source for his research paper, we are producing the same plastic cups by pressure forming and vacuum forming to increase our production capacity and the supply chain. As a result, we state that we provide the information required for the work from each of them.

Sincerely,

General Manager, BA Manufacturing PLC

Addis Ababa, Ethiopia

CamScanner

Appendix II

Recorded data for wastage produced in a week using the two methods of plastic cup manufacturing —Servo cup making machine (VF)and Tilt cup making machine(PF), respectively.

Day	Product per Pc	Wastage per kg in VF
1	94811	3.15kg
2	257022	0.3kg + 0.2kg
3	115377	1.85kg + 1.75kg
4	43575	0.28kg
5	6257	0kg

Day	Product per Pc	Wastage per kg in PF
1	17406	2.15kg
2	54020	3.00kg
3	32742	2.10kg
4	45774	0.00kg
5	3870	0.00kg

Desu Taye Sime

HR & Property Mgt Head

Appendix III

The data of manufacturing time and energy consumption of the two methods of plastic cup manufacturing —vacuum forming (VF) and pressure forming (PF), were taken from the machine by capturing photo using mobile phone camera, respectivly.

13560 P/hr

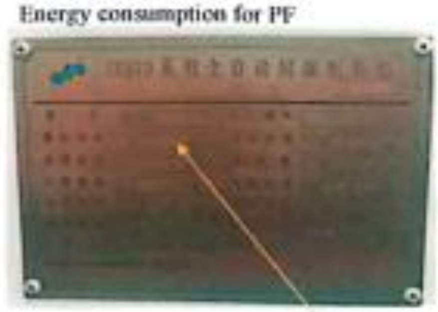
Manufacturing time for VF

Manufacturing time for PF

11340 P/hr

Energy consumption for VF

Energy consumption for PF



150KW

90KW

Appendix IV

Over all data verification table for all information taken from the BA-Manufacturing PLC of the two methods of plastic cup manufacturing —vacuum forming (VF) and pressure forming (PF). respectivly.

Parameters	Vacuum Forming [Automatic servo cup making machine]	Pressure Forming [Automatic tilt cup making machine]
Raw material type	Polypropylene	Polypropylene
Manufacturing time	13560 pc / hr.	11340 pc / hr.
Wastage	7.53kg/517042pc	7.25kg/153812pc
Energy consumption	90kw	150kw
Manufacturing cost per part	2.12 Br	2.20 Br
Skill for Operator training Skill for technician training	Six month Eight month	Eight month Ten month
Weight per part	5.00 g	5.00 g
Raw material cost	67.2 Br/ kg	67.2 Br/ kg

Desu Taye Sime

& Property Mgt Head

Appendix V

Recoded data for the site-risk assessment sheet in a week using the two methods of plastic cup manufacturing

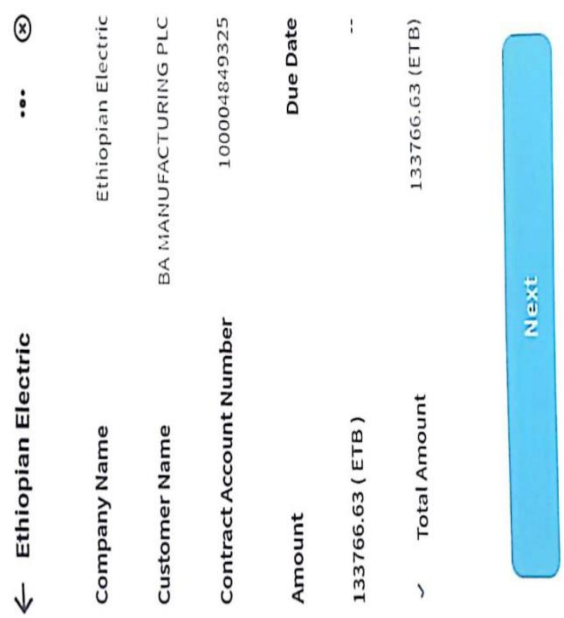
Risks		Date	Servo cup making machine				Tilt cup making machine				Remark
		23/01/24-27/01/24	Simple	Medium	Higher	Nothing	Simple	Medium	Higher	Nothing	
1	Injury	〃				✓	✓				
2	Slips & falls	〃				✓				✓	
3	Accident	〃				✓				✓	
4	Wounds	〃	✓							✓	
5	Illness from stress	〃	✓							✓	
7	infections	〃		✓			✓				
8	Incidents	〃				✓				✓	

Desu Teye Sime

HR & Property Mgt Head

Appendix VI

Recorded payment bill for power consumption



TIN No. 0000030603
VAT Reg. Date 01/01/2003
P.O.Box 1047 Addis Ababa
Tel . 251(0) 115 505 678

የክፍያ መረጃ/Transaction information

የከፋይ ስም/Payer Name	BA MANUFACTURING PLC
የከፋይ ቴሌብር ቁ./Payer telebirr no.	944808384
የከፋይ አካውንት አይነት/Payer account type	Individual Customer
የከፋይ ቲን ቁ./ Payer TIN No	0039553109
የገንዘብ ተቀባይ ስም/Credited Party name	Ethiopian Electric Utility
የገንዘብ ተቀባይ ቴሌብር ቁ./Credited party account no	5030
የክፍያው ሁኔታ/transaction status	Completed
የክፍያው ማዘዣ ቁጥር/Paid reference number	100004849325 BA MANUFACTURING PLC

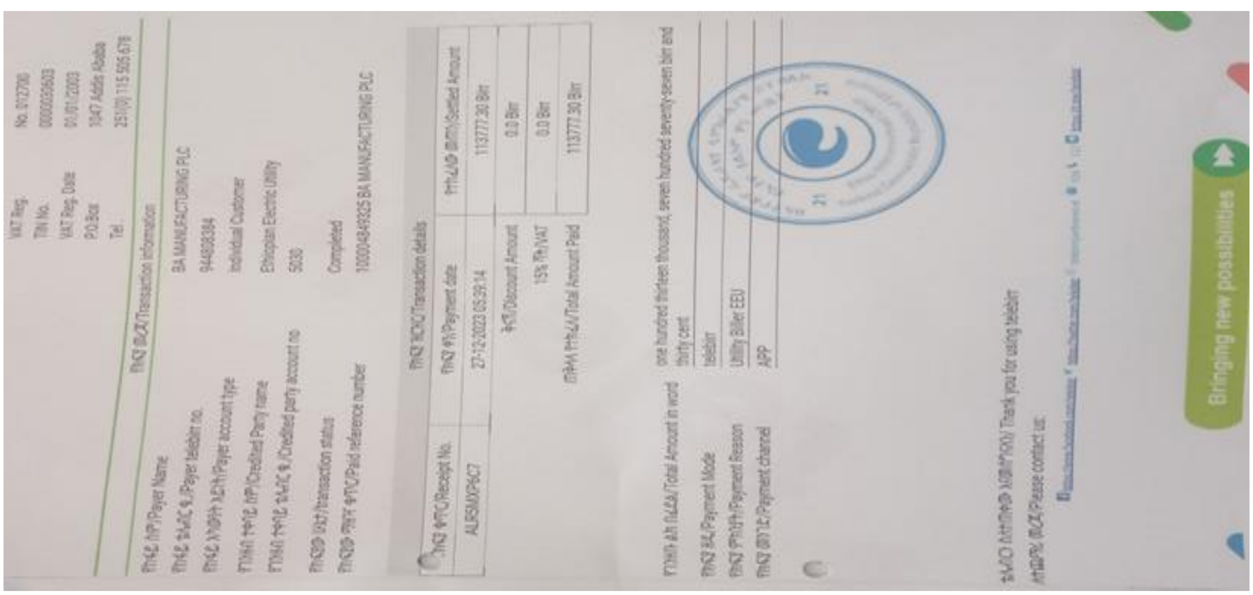
የክፍያ ዝርዝር/Transaction details

የክፍያ ቁጥር/Receipt No.	የክፍያ ቀን/Payment date	የተከፈለው መጠን/Settled Amount
BAP2VP2KV8	25-01-2024 09:40:52	133766.63 Birr
	ቅናሽ/Discount Amount	0.0 Birr
	15% ቫት/VAT	0.0 Birr
	የአገልግሎት ክፍያ/service fee	1.00
	ጠቅላላ የተከፈለ/Total Amount Paid	133767.63 Birr

የገንዘቡ ልክ በፊደል/Total Amount in word	one hundred thirty-three thousand, seven hundred sixty-seven birr and sixty-three cent
የክፍያ ዘዴ/Payment Mode	telebirr
የክፍያ ምክንያት/Payment Reason	Utility Biller EEU
የክፍያ መንገድ/Payment channel	APP

ቴሌብርን ስለተጠቀሙ እናመሰግናለን/ Thank you for using telebirr
ለተጨማሪ መረጃ/Please contact us:
https://www.facebook.com/telebirr https://twitter.com/telebirr https://t.me/telebirr

Bringing new possibilities



VAT Reg. No. 012700
TIN No. 0000030603
VAT Reg. Date 01/01/2003
P.O.Box 1047 Addis Ababa
Tel. 251(0) 115 505 678

Transaction information

Payer Name	BA MANUFACTURING PLC
Payer telebirr no.	944808384
Payer account type	Individual Customer
Credited Party name	Ethiopian Electric Utility
Credited party account no	5030
transaction status	Completed
Paid reference number	100004849325 BA MANUFACTURING PLC

Transaction details

Receipt No.	Payment date	Settled Amount
AUF5MXP6C7	27-12-2023 05:39:14	113777.30 Birr
	Discount Amount	0.0 Birr
	15% VAT	0.0 Birr
	Total Amount Paid	113777.30 Birr

Total Amount in word	one hundred thirteen thousand, seven hundred seventy-seven birr and thirty cent
Payment Mode	telebirr
Payment Reason	Utility Biller EEU
Payment channel	APP

Thank you for using telebirr
Please contact us:

Bringing new possibilities

Appendix VII

A statistical frequency counting method has been performed under the three pillars (Economic (Ec), Environmental (En) and Social (Sc)) in respective indicators with their frequency of usage.

Manufacturing Cost(Ec_1): Unit Production Cost(Ec_{11}), Actual Machining Cost(Ec_{12}), Cost of by-product treatment(Ec_{13}), Governmental Policies(Ec_{14}), Machine Tool Usage Cost(Ec_{15}), Administrative Burdon(Ec_{16}), Public authority(Ec_{17}), Property right(Ec_{18}), Cutting and Lubrication Fluid Cost(Ec_{19}).	Machining Performance(Ec_2): Surface Roughness(Ec_{21}), Cutting Quality(Ec_{22}), Cutting Temperature(Ec_{23}), Machining induced variations(Ec_{24}),	Production Efficiency(Ec_3): Production rate (Ec_{31}), Cutting Power(Ec_{32}), Material Removal Rate(Ec_{33}),	Process Improvement(Ec_4): Process Management (Ec_{41}), Continuous improvements of existing processes (Ec_{42}), Improvement of material/energy consumption (Ec_{43}), Performance Measurement (Ec_{44}).

Energy Consumption(En_1): Energy consumed(En_{11}), Renewable and non-renewable resource consumed(En_{12}), Idle energy(En_{13}), Energy Intensity(En_{14}),	Types of material(En_2): Raw materials (En_{21}), Material composition (En_{22}), Usability of hazardous material (En_{23}), re-usability (En_{24}), Packaging (En_{25}), recyclability (En_{26}), Distance from source (En_{27}).	Waste and Pollution(En_3): Waste Management (En_{31}), Weight of release from production process(En_{32}), Climate effect(En_{33}), reuse ratio(En_{34}), Pollution impact on ozone layer(En_{35}), Wastage and Spill over during production(En_{36}), Mass of coolant loss(En_{37}), Weight of transfers to sewage from production process(En_{38}).	Water Consumption(En_4): Water Intensity (En_{41}), Amount of re used water (En_{42}), Consumption of water per unit of output (En_{43}), Source of water for the process (En_{44}). Government Rules and Regulation(En_5): Existing Environmental Regulations (En_{51}), Land usage (En_{52}).

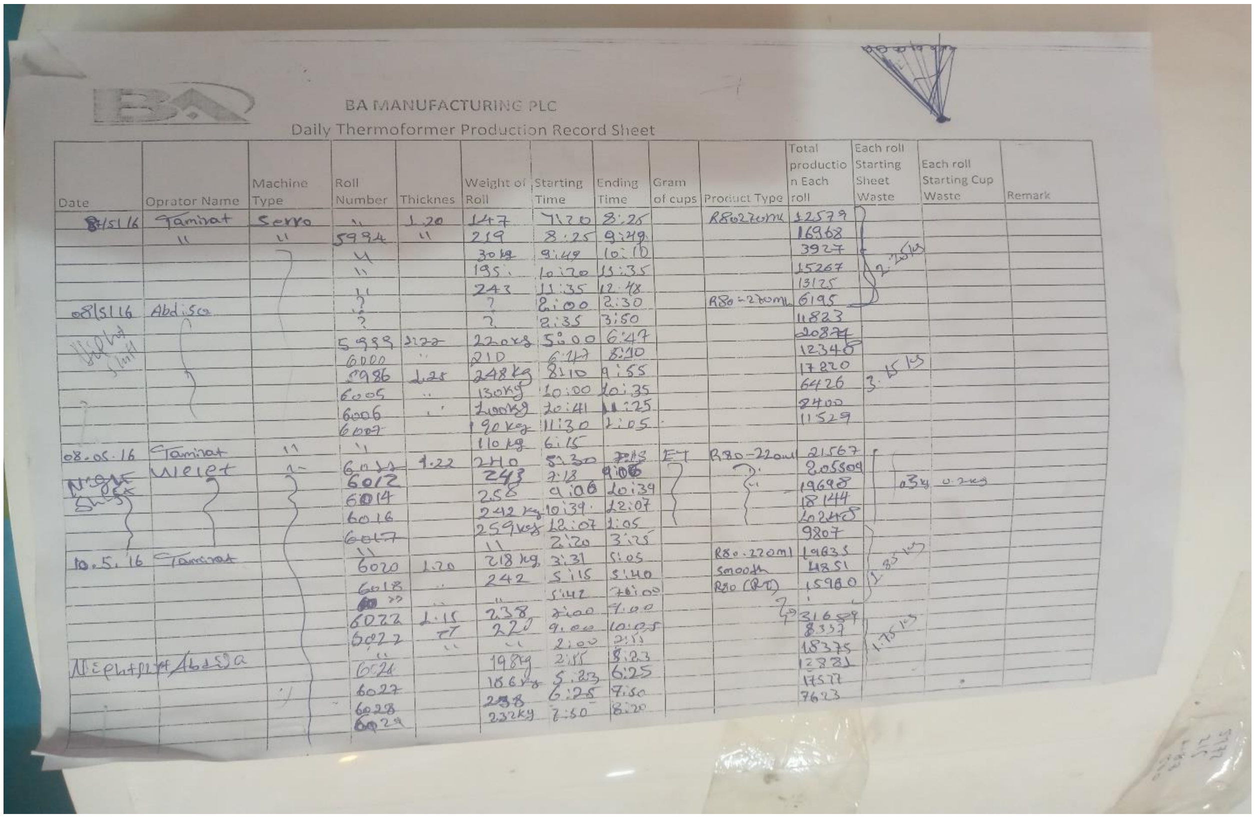
Health Issues(Sc_1): Worker Health (Sc_{11}), Noise Level(Sc_{12}), Health related absenteeism rate(Sc_{13}), Compliance with regulatory requirements imposed(Sc_{14}), Admitted level of emissions and waste from machining operations(Sc_{15}).	Safety Issues(Sc_2): Worker Safety(Sc_{21}), Exposure to toxic chemicals(Sc_{22}), Near Misses(Sc_{23}), Exposure to high energy components(Sc_{24}), Number of occupational accidents(Sc_{25}), Risk Level, Ergonomic Design(Sc_{26}).	Labor Issues(Sc_3): Labor Relations (Sc_{31}), Hourly Wages (Sc_{32}), Working Hours (Sc_{33}), Workload (Sc_{34}), Community Engagement (Sc_{35}), Local Employment (Sc_{36}).	Workforce Training(Sc_4): Training and Education (Sc_{41}), Average Number of Hours of training per operator (Sc_{42}), Required Skill Level (Sc_{43}).

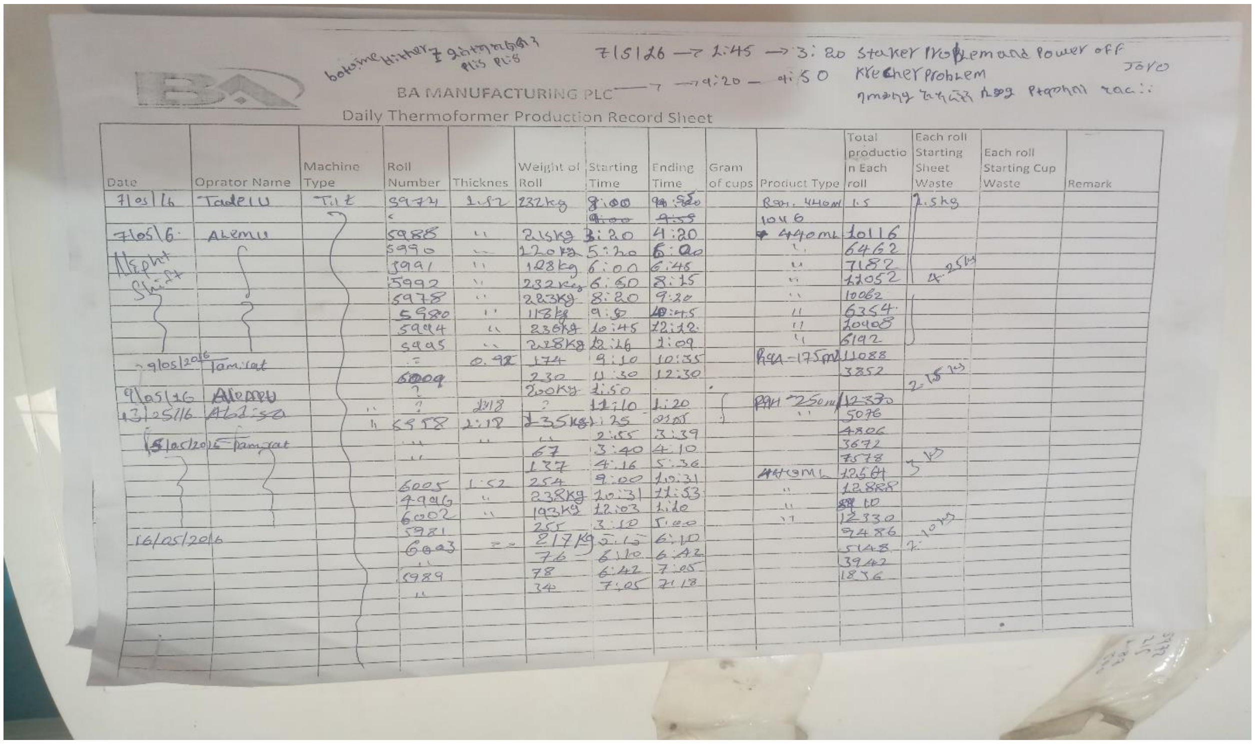
Appendix VIII

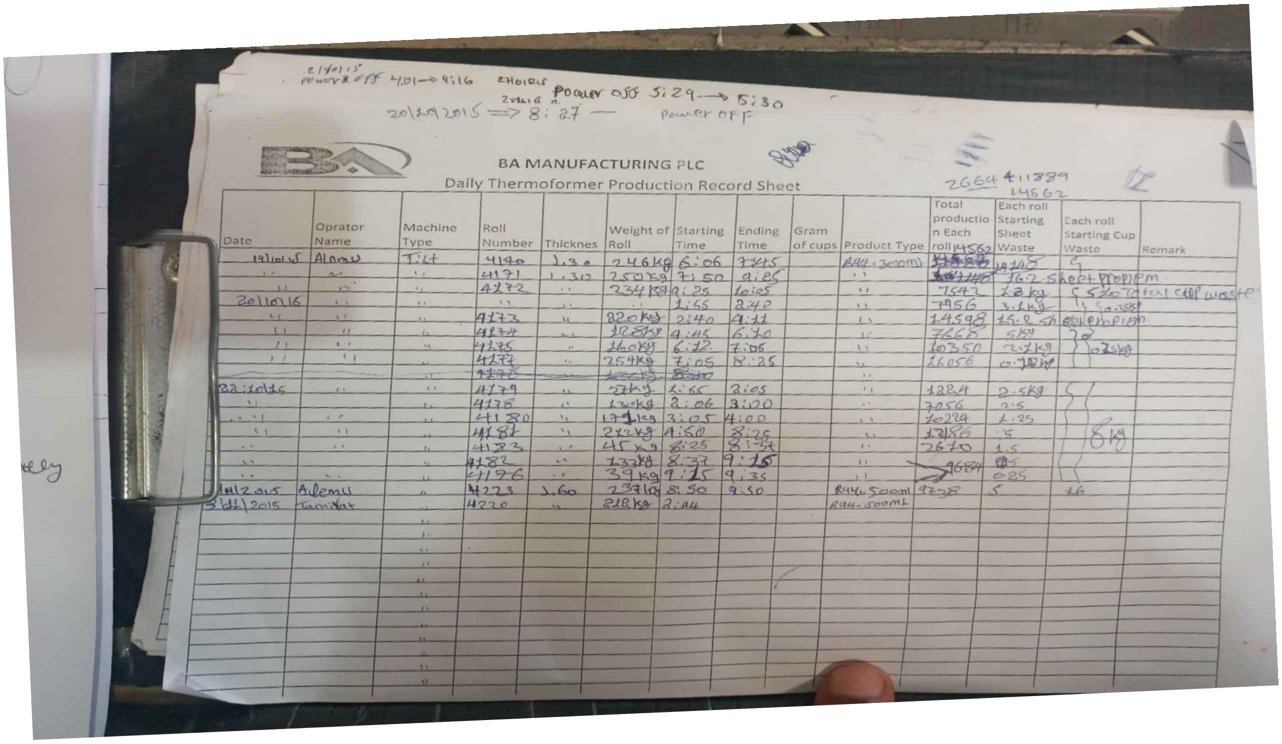
A statistical frequency-counting table

Indicators			Reference											
			[16]	[22]	[23]	[24]	[25]	[26]	[27]	[28]	[29]	[30]	[31]	Frequency
Ec_1	En_1	Sc_1		†	†	†	†	†	†		†		†	8
Ec_{11}	En_{11}	Sc_{11}		†	†	†	†	†			†			6
Ec_{12}	En_{12}	Sc_{12}	†		†		†		†	†	†		†	7
Ec_{13}	En_{13}	Sc_{13}	†	†		†						†		4
Ec_{14}	En_{14}	Sc_{14}					†			†				2
Ec_{15}		Sc_{15}		†		†								2
Ec_{16}					†		†				†			3
Ec_{17}								†	†			†		3
Ec_{18}											†		†	2
Ec_{19}							†							1
Ec_2	En_2	Sc_2	†	†	†	†	†	†	†	†	†	†	†	11
Ec_{21}	En_{21}	Sc_{21}	†	†	†	†		†	†	†	†	†	†	10
Ec_{22}	En_{22}	Sc_{22}	†	†	†		†			†	†	†		7
Ec_{23}	En_{23}	Sc_{23}			†	†	†		†					4
Ec_{24}	En_{24}	Sc_{24}		†	†	†				†				4
	En_{25}	Sc_{25}					†	†						2
	En_{26}	Sc_{26}			†	†								2
	En_{27}								†					1
Ec_3	En_3	Sc_3	†	†	†	†	†	†	†	†	†		†	10
Ec_{31}	En_{31}	Sc_{31}		†		†	†	†	†	†	†	†	†	9
Ec_{32}	En_{32}	Sc_{32}	†		†			†	†	†				5
Ec_{33}	En_{33}	Sc_{33}		†		†	†							3
	En_{34}	Sc_{34}	†	†										2
	En_{35}	Sc_{35}						†	†	†				3
	En_{36}	Sc_{36}			†	†								2
	En_{37}						†							1
	En_{38}								†					1
Ec_4	En_4	Sc_4		†	†	†			†	†	†	†		7
Ec_{41}	En_{41}	Sc_{41}		†	†	†	†		†	†	†			7
Ec_{42}	En_{42}	Sc_{42}			†	†	†							3
Ec_{43}	En_{43}	Sc_{43}	†	†										2
Ec_{44}	En_{44}							†						1
	En_5			†					†	†	†			4
	En_{51}	†			†			†		†				4
	En_{52}								†		†			2

Daily machine attendance sheets







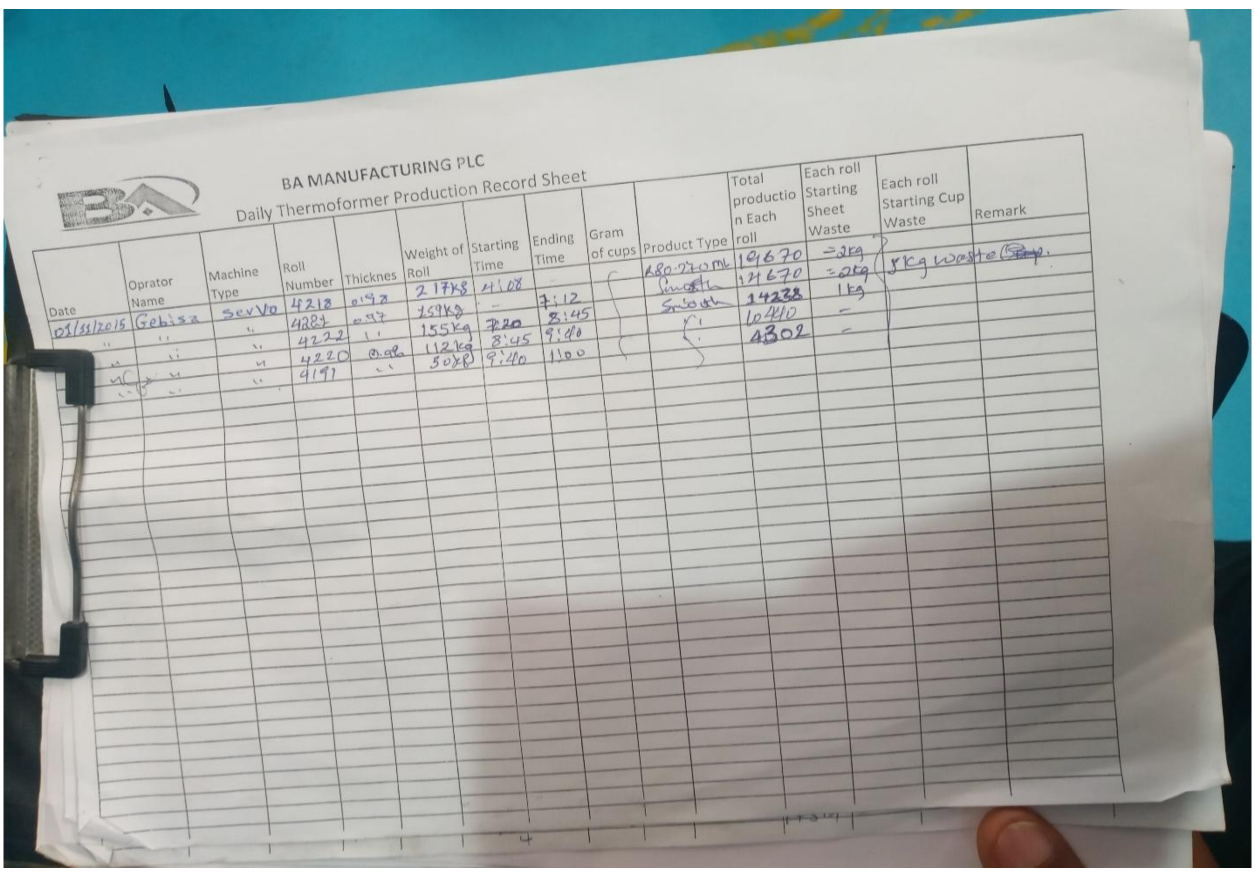
2/10/15 power off 4:01→4:16
2/10/15 power off 5:29 → 5:30
20/10/2015 ⇒ 8:27 — power off

BA MANUFACTURING PLC

Daily Thermoformer Production Record Sheet

2664 411889 14562

Date	Oprator Name	Machine Type	Roll Number	Thicknes	Weight of Roll	Starting Time	Ending Time	Gram of cups	Product Type	Total production Each roll	Each roll Starting Sheet Waste	Each roll Starting Cup Waste	Remark
19/10/15	Alemu	Tilt	4170	1.30	246kg	6:06	7:45		R94-300ml	[illegible]	[illegible]	5	
"	"	"	4171	1.30	250kg	7:50	9:25		"	[illegible]	16.2 sheet problem		
"	"	"	4172	"	234kg	9:25	10:05		"	7542	1.8 kg	5% total cup waste	
20/10/16	"	"	"	"	"	1:55	2:40		"	7956	3.1kg	5 [illegible]	
"	"	"	4173	"	820kg	2:40	4:11		"	14598	15.2 sheet problem		
"	"	"	4174	"	128kg	4:45	6:40		"	7668	5kg		
"	"	"	4175	"	160kg	6:12	7:06		"	10350	2.1kg	0.25kg	
"	"	"	4177	"	254kg	7:05	8:25		"	16056	[illegible]		
		"	~~4178~~		~~[illegible]~~	~~[illegible]~~			"				
22/10/15	"	"	4179	"	27kg	1:55	2:05		"	1224	2.5kg		
"		"	4178	"	130kg	2:06	3:00		"	7056	2.5		
"	"	"	4180	"	171kg	3:05	4:00		"	10224	1.25		
"	"	"	4181	"	242kg	4:50	8:25		"	12186	.5	8kg	
"	"	"	4183	"	45kg	8:25	8:34		"	2670	1.5		
"		"	4182	"	133kg	8:37	9:15		"	9684	0.5		
"	"	"	4176	"	39kg	9:15	9:35		"		0.25		
1/11/2015	Alemu	"	4223	1.60	237kg	8:50	9:30		R94-500ml	9738	5	16	
3/11/2015	Tamirat	"	4220	"	218kg	2:44			R94-500ml				



BA MANUFACTURING PLC

Daily Thermoformer Production Record Sheet

Date	Oprator Name	Machine Type	Roll Number	Thicknes	Weight of Roll	Starting Time	Ending Time	Gram of cups	Product Type	Total production Each roll	Each roll Starting Sheet Waste	Each roll Starting Cup Waste	Remark
01/11/2015	Gebisa	servo	4218	0.98	217kg	4:08	—		480-770ml	19670	=2kg	8kg waste [illegible]	
"	"	"	4284	0.97	159kg	—	7:12		Smooth	14670	=2kg		
"	"	"	4222	"	155kg	7:20	8:45		Smooth	14238	1kg		
"	"	"	4220	0.96	112kg	8:45	9:40		"	10410	—		
"	"	"	4191	"	50kg	9:40	11:00			4302	—		

BA MANUFACTURING PLC

Date: 16/12/2024

Acknowledgement Letter

We hereby acknowledge that we are aware of and have evidence of Abebaw's thesis work within our company, as well as proof of the testing of his model. We confirm that all necessary approvals have been granted for this process and that operational guidelines are being followed throughout.

Thank you for your continued trust in our company, and we look forward to doing business with you in the future.

Sincerely,

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Desu Taye Sime
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HR & Property Mgt Head

BA Manufacturing PLC
0911 20 18 55