

Optimizing Production Waste and Enhancing Operational
Efficiency through Integrated Lean Management and Reliability
Analysis: A Case Study of National Tobacco Enterprise

By:

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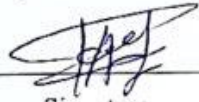
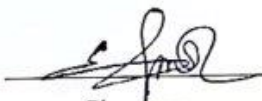


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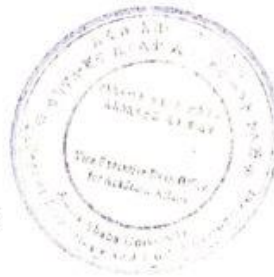
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Approval Sheet

Optimizing Production Waste and Enhancing Operational Efficiency through
Integrated Lean Management and Reliability Analysis: A Case Study of National
Tobacco Enterprise
By: Fasil Asegdew

This is to certify that the thesis prepared by Fasil Asegdew entitled: Optimizing Production Waste and Enhancing Operational Efficiency through Integrated Lean Management and Reliability Analysis: A Case Study of National Tobacco Enterprise is submitted for the approval of dissertation work for the fulfillment of MSc in Mechanical Engineering (Industrial Engineering). It complies with the university's regulations and meets the accepted standards with respect to originality and quality.

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Author Declaration

I, Fasil Asegdew, hereby declare that this thesis entitled “*Optimizing Production Waste and Enhancing Operational Efficiency through Integrated Lean Management and Reliability Analysis: A Case Study of National Tobacco Enterprise*” is my original work and has not been submitted for any other degree or publication.

This study conducted under the supervision of Dr. Kassu Jilcha at Addis Ababa University, specifically within the College of Technology and Built Environment (CTBE) School of Mechanical and Industrial Engineering (SMIE).

All sources of information used in this work have been properly acknowledged and all data collected from NTE was used with permission and confidentiality safeguards.



Fasil Asegdew

Date

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List of Abbreviations

- 5S:** Sort, Set in Order, Shine, Standardize, and Sustain
- 6M:** Machine, Method, Man (People), Material, Measurement, and Environment
- ALT:** Accelerated Life Testing
- AM:** Autonomous Maintenance
- Assoc. prof.:** Associate Professor
- C/T:** Changeover Time
- CFTs:** Cigarette Filter Tips
- CI:** Continuous Improvement
- CMMS:** Computerized Maintenance Management System
- CT:** Cycle Time
- CTBE:** College of Technology and Built Environment
- Det:** Detection
- DMAIC:** Define, Measure, Analyze, Improve, Control
- DPMO:** Defects Per Million Opportunities
- ERP:** Enterprise Resource Planning
- FG:** Finished Goods
- FMEA:** Failure Mode and Effects Analysis
- FRACAS:** Failure Reporting, Analysis, and Corrective Action Systems
- FTA:** Fault Tree Analysis
- HVAC:** Heating, Ventilation, and Air Conditioning
- IoT:** Internet of Things
- JIT:** Just-In-Time
- JTI:** Japan Tobacco International
- Kaizen:** Continuous Improvement
- Kanban:** Kanban System
- KPIs:** Key Performance Indicators
- Lean:** Lean Management
- Lean-RCM:** Lean Reliability-Centered Maintenance
- MES:** Manufacturing Execution System
- MR:** Machine Reliability
- MSc:** Masters in Science

MTBF: Mean Time Between Failures
MTTR: Mean Time To Repair
NTE: National Tobacco Enterprise
NTM: Non-Tobacco Material
Occ: Occurrence
OEE: Overall Equipment Effectiveness
OP: Operational Performance
PM : Process Management
PM : Preventive Maintenance
Poka-Yoke: Mistake-Proofing
RBD: Reliability Block Diagrams
RCA: Root Cause Analysis
RCM: Reliability-Centered Maintenance
RMC: Ready-Made Cigarettes
RPN: Risk Priority Number
RUL: Remaining Useful Life
SD: Standard Deviation
Sev: Severity
Six Sigma: Six Sigma (a methodology for defect reduction)
SMED: Single-Minute Exchange of Die
SMIE: School of Mechanical and Industrial Engineering
SOPs: Standard Operating Procedures
SPC: Statistical Process Control
TPS: Toyota Production System
TPM: Total Productive Maintenance
VSM: Value Stream Mapping
WIP: Work-in-Process
WWII: World War II

ABSTRACT

Global manufacturing consistently grapples with significant production waste and operational inefficiencies, detrimentally affecting profitability, competitiveness, and sustainability. This thesis, from an industrial engineering standpoint, critically examines these pervasive challenges within the National Tobacco Enterprise (NTE), focusing specifically on its Make-Pack department. Quantitative analysis of 30-month operational data revealed chronic underperformance: cigarette reject rates averaged 5.02% (exceeding a 3% target), Non-Tobacco Material (NTM) waste reached 3.38% (above a 1% target), and Overall Equipment Effectiveness (OEE) consistently fell below target at 35.86%. These metrics underscore a critical need for integrated improvement strategies, as isolated Lean Management or Reliability-Centered Maintenance (RCM) interventions have proven insufficient. To address this, a comprehensive mixed-methods research approach was employed. This involved rigorous statistical analysis of production KPIs, Value Stream Mapping (VSM) to identify process bottlenecks, and in-depth equipment reliability assessments using Failure Mode and Effects Analysis (FMEA) and Root Cause Analysis (RCA). Qualitative data from interviews further contextualized findings, revealing reactive maintenance cultures and skill gaps. A key finding established a quantifiable link: equipment unreliability, reflected in low OEE, accounted for 50.8% of reject rate variability and 78.1% of NTM yield variability. Root causes spanned inadequate preventive maintenance, sensor control deficiencies, and insufficient operator training. This study proposes and empirically validates an integrated Lean-RCM framework, offering a synergistic solution for sustainable waste optimization and enhanced operational efficiency within complex manufacturing environments like NTE, setting a benchmark for the industry.

Keywords: Lean Management, Reliability, Overall Equipment Effectiveness , Waste Reduction, Production Efficiency, Failure Mode and Effects Analysis, Value Stream Mapping, Tobacco Industry.

Chapter One

Problem Approach

1.1 Introduction

Almost every manufacturing industry around the globe faces the problem of production waste and its negative impacts on both economic and environmental performance. In materials-intensive sectors such as tobacco production where there are tight regulations, the optimization of material and equipment usage becomes vitally important. Waste also contributes to higher operational costs and stops businesses from working towards their sustainability goals, which have become key priorities for many businesses with a competitive landscape (De et al., 2020). It requires that industries embrace solutions that venture beyond conventional approaches and explore new structures that epitomize the synergy of lean manufacturing and reliability analysis. This integration guarantees efficiency in processes, minimizes waste, and improves equipment dependability, enabling profitability and sustainability.

Lean manufacturing is a well-known methodology with a long history in many industries aimed at cutting waste and improving processes (Jayswal et al., 2017). The primary concept of lean manufacturing is the elimination of nonvalue adding activities resulting in higher productivity, cost reduction and higher quality. By focusing on maximizing value for customers while minimizing waste, lean manufacturing creates a culture of continuous improvement. Lean manufacturing uses various tools and techniques to achieve these goals, such as Value Stream Mapping (VSM), Just-In-Time (JIT) production, and continuous improvement practices. One of the main ideas of lean manufacturing is using Value Stream Mapping, which helps organizations visualize their processes and find places where they can be more efficient. By mapping the flow of materials and information, businesses can find bottlenecks, redundancies, and inefficiencies in their operations. This visual tool not only helps identify waste but also encourages communication among team members, promoting a collaborative approach to solving problems.

In the tobacco industry, applying VSM as part of a Business Excellence Model can help deal with the unique challenges this sector faces, such as managing delicate raw materials and following regulatory requirements. Tobacco production has many stages,

from sourcing raw materials to processing and packaging, each providing chances for waste reduction. By implementing lean principles, tobacco manufacturers can streamline their operations, cut lead times, and improve product quality. Also, using Just-In-Time production can help lower inventory costs and reduce the risk of material waste from spoilage or obsolescence.

While lean manufacturing focuses on waste prevention, it often overlooks the importance of machine reliability for stable operations. Reliability analysis estimates how likely equipment is to fail and evaluates its impact on production, making it crucial for industries that rely heavily on machinery (Kumar et al., 2022).the dependence on machinery in tobacco manufacturing means that any equipment failure can cause significant disruptions, affecting production schedules and raising costs. Research has shown that systematic reliability methods, such as Failure Modes and Effects Analysis (FMEA) and improved preventive maintenance plans, can greatly reduce machine downtime and enhance overall production efficiency (Jiang et al., 2023).However, despite the proven benefits of reliability analysis, there has been little research on the combined use of lean principles and reliability analysis in the context of tobacco manufacturing, especially in developing countries like Ethiopia.

The need for integrated waste elimination and equipment reliability strategies is well shown by the case of the National Tobacco Enterprise (NTE), a major player in the Ethiopian tobacco industry. NTE currently faces significant operational inefficiencies, with material waste rates between 3% to 8% and frequent instances of idle machines.these inefficiencies not only lead to higher costs but also hinder the company's ability to compete effectively in the market. current maintenance practices and process workflows at NTE are not enough to solve these problems, resulting in increased production costs and lower throughput. previous studies have usually looked at production efficiency through either lean manufacturing or reliability analysis as separate perspectives. However, the combined application of these methodologies has not been explored in tobacco manufacturing, creating both a theoretical and practical gap in the literature.this gap offers an opportunity for research to develop a more comprehensive approach that integrates lean manufacturing principles with reliability analysis to improve production processes at NTE.

This research aims to fill these gaps by combining lean manufacturing and reliability analysis to enhance the production processes at NTE.the theoretical importance of this

study lies in its contribution to understanding how two well-established methodologies can be merged to create a holistic approach to waste reduction and operational efficiency. By integrating these strategies, the research seeks to provide a framework that can be applied not just in the tobacco sector but also in other manufacturing industries facing similar challenges. practically, this research is important as it provides actionable insights to the tobacco sector and other manufacturing industries trying to balance cost-effectiveness with sustainability. the findings from this study show how incorporating lean and reliability strategies can lead to measurable improvements in material waste reduction, equipment uptime, and overall production effectiveness.

To achieve the research objectives, a mixed-methods approach was used.this involve both qualitative and quantitative data collection methods, including case studies, interviews with industry experts, and analysis of production metrics at NTE. By gathering comprehensive data, the research identify specific areas where lean manufacturing and reliability analysis can be effectively integrated to address the challenges faced by NTE.this approach not only provide a detailed understanding of the current operational landscape but also help identify best practices that can be adopted across the industry.through the lens of NTE, this study seeks to demonstrate how integrating lean manufacturing principles and reliability analysis can lead to significant gains in operational performance. Expected outcomes include a reduction in material waste, improved equipment uptime, and enhanced overall production effectiveness. By applying lean principles like Value Stream Mapping, NTE can identify and eliminate wasteful practices, leading to lower material waste rates.the implementation of reliability analysis techniques, such as FMEA and preventive maintenance plans, improve machine reliability and reduce downtime.

In conclusion, the challenges of production waste and equipment reliability in the tobacco manufacturing industry require innovative solutions that go beyond traditional methods. By integrating lean manufacturing and reliability analysis, this research aims to provide a framework that enhances operational efficiency, reduces waste, and promotes sustainability.the case of the National Tobacco Enterprise serves as a valuable context for exploring these strategies, with the potential to yield insights applicable to other manufacturing sectors. ultimately, this study hopes to contribute to the ongoing conversation about sustainable manufacturing practices and provide actionable strategies for industries facing the complexities of modern production environments.

By addressing both waste management and equipment reliability, this research aims not only to improve the bottom line for manufacturers but also to support broader efforts toward environmental sustainability and responsible production practices.

1.2 Background and Justification

The focus of this study is the optimization of production waste in the tobacco manufacturing process through the integration of reliability analysis and lean systems. The primary aim is to address production inefficiencies and waste reduction within the National Tobacco Enterprise (NTE), Ethiopia's largest tobacco manufacturer. This research is particularly significant in industries where waste adversely affects profitability, operational efficiency, and environmental sustainability. By using lean manufacturing principles together with reliability analysis, this study aims to improve operations, boost productivity, and effectively reduce waste.

The tobacco industry significantly contributes to Ethiopia's economy in general and the government through the important contribution of NTE towards governmental revenues, employments, and socioeconomic developments in regions where it operates. The challenges of this industry are increasingly worsening operational efficiencies through regulatory pressures and strengthening global competition (Shah, Chandrasekaran, & Linderman, 2008). High levels of production waste, particularly cigarette reject rates, underscore the urgent need for systematic improvements. This research focuses on utilizing lean manufacturing methodologies combined with reliability-centered maintenance to address these inefficiencies. By reducing production waste, the study not only aligns with global sustainable manufacturing goals but also supports Ethiopia's economic growth by enhancing the operational efficiency of one of its most prominent enterprises.

The National Tobacco Enterprise (Ethiopia) Share Company was founded in 1942 and has been one of the major players in the industrial sector in Ethiopia. It initially produced its first cigarette brand called "Nigusu," while major restructuring took place in 1981, and it was restructured in 1992 under Proclamation No. 37/1992, giving the company exclusive rights to manufacture, distribute, import, and export tobacco products. The turning point came in 2016 when JT acquired a 79% stake in NTE with an investment of USD 1 billion, bringing international investment and operational expertise. Today, the company pays upwards of Birr 700 million Birr annually in taxes

and employs in excess of 4,500 workers, permanent and temporary. However, the company has more severe issues in the manufacturing waste management sector to maintain particular levels of product quality.

The literature indicates that there are prospects for efficiently reducing waste and increasing the operational effectiveness of an organization through lean management and Reliability analyses . According to (Aucasime-Gonzales et al. (2020) and (Chaeron et al. (2020), lean thinking has the potential to eliminate waste and add value to each process of manufacturing. Similarly, (Khasanah et al. (2021) highlights the contribution of RCM in terms of enhancing equipment reliability and reducing downtimes. Recent research indicates that, with the incorporation of lean methodology supported by advanced maintenance strategies, significant improvement can be achieved in operational performance across industries (Mendes et al., 2022). However, the application of these strategies within the tobacco industry, particularly in Ethiopia, is not well explored, hence this research opportunity to fill the gap.

Selection of the topic has been driven by the dire need for NTE to address operational inefficiencies and re-align itself to global best practices. High reject rates, due to equipment malfunction, inefficient material handling, and inconsistent quality control, call for structured methodologies in lean manufacturing and reliability analysis in optimizing operations. According to (Ananthukrishna ,2019), in addition to this research aligns with global trends advocating for sustainable manufacturing practices, making it both timely and relevant.

The choice of NTE as a case study is based on its critical position in the economy of Ethiopia and operational challenges that have continually confronted the enterprise. It being the largest manufacturer of tobacco products in the country, it contributes a great deal to government revenue and livelihood for thousands of workers. However, its operational inefficiencies, as evidenced by an 6.74% cigarette reject rate in 2023, present an opportunity for transformation through the application of lean and reliability-centered strategies .this case offers a unique context to explore the application of advanced methodologies in a developing economy, contributing to both the academic discourse and practical advancements in the field.

In summary, this research focuses on integrating lean manufacturing and reliability analysis to address production inefficiencies and waste reduction within the context of NTE.the importance of the topic is underscored by NTE's critical role in Ethiopia's

economy and the global emphasis on sustainable manufacturing practices. By leveraging existing research on lean methodologies and maintenance strategies, the study addresses a critical gap in their application to the tobacco industry. The selection of NTE as a case study ensures practical relevance and provides insights into optimizing operations in developing economies.

1.3 Problem Statement

In the manufacturing sector, operational inefficiencies and waste from rejection are critical problems that can really affect the company profit and competitiveness. National Tobacco Enterprise (NTE), a major tobacco manufacturer in Ethiopia, is encountering significant challenges within its Make-Pack department, the final stage of cigarette manufacturing and packaging. The primary issue at hand is excessive material rejection, the company data shows that NTE's material rejection rate has been going up and down between 4% and 7% in the last two years, always higher than the company's target of 3% and the global industry standard of 2-3% that other companies using lean manufacturing practices have. This high waste rate makes profit lower by using more raw materials and foreign currency, and it raises environmental issues, especially with more regulations and expectations for sustainability (De et al., 2020). The waste problem in the Make-Pack department is complex and shows itself through high reject rates of cigarettes and too much Non-Tobacco Material (NTM) waste. The company data reveals that cigarette rejects, which do not meet quality standards, cause a lot of waste by throwing away valuable tobacco and its packaging materials. An internal report from 2022 reveals the reject rate is now 6%, which is much higher than the company's target of 3%. Also, the data shows that performance is not consistent throughout the year, with monthly reject rates changing a lot, in May 2022, the reject rate was very high at 8.49%, far above the target. Even if some improvements are seen in 2023 compared to 2022, but NTE still has trouble keeping a low reject rate all year round, with seasonal trends showing higher reject rates at the start and end of the year.

The company data shows that NTM waste includes imported materials like label reels, end labels, parceling straps, pre-cut reel straps, aluminum foil, polypropylene film, polypropylene tear tape, and glue for labels. These packaging materials are often thrown away because they are overused, damaged, or because of process inefficiencies, making the waste problem even worse.

Another big issue causing inefficiency is the frequent breakdown of machines and long downtimes. The internal reports from NTE show many time machine failures, which badly affect production output and efficiency. The data shows that these breakdowns often cause unplanned stoppages, which impact not only waste generation but also overall performance. The company Overall Equipment Effectiveness (OEE) trend shows big operational challenges that hurt performance and profit. OEE data shows big differences, going from a low of 25.76% in September 2022 to a high of 47.36% in October 2023, always below the company's target of 44.5%. Seasonal trends show improvements in the middle of the year, but declines at the start and end of the year, suggesting problems with machine maintenance, downtime, and not using resources well. These inefficiencies lead to more production disruptions and less overall output. The company Overall Equipment Effectiveness (OEE) data shows big operational challenges that hurt performance and profit. OEE data shows big differences, going from a low of 25.76% in September 2022 to a high of 47.36% in October 2023, always below the company's target of 44.5%. Seasonal trends show improvements in the middle of the year, but declines at the start and end of the year, suggesting problems with machine maintenance, downtime, and not using resources well. These inefficiencies lead to more production disruptions and less overall output.

Table 1.1 Descriptive Statistics of Key Performance Indicators inefficiencies

KPI	Average Performance (M)	Target	Deviation from Target	Statistical Significance (p-value)
Cigarette Reject Rate (%)	5.02%	3.20%	+1.82% (Excessive)	< .001
NTM Waste Rate (%)	3.38%	1.00%	+2.38% (Excessive)	< .001
Overall Equipment Effectiveness (OEE) (%)	35.86%	43.90%	-8.04% (Shortfall)	< .001
Production Yield (%)	89.40%	94.00%	-4.60% (Shortfall)	< .001

Source: (NTE data analytics department)

Additionally, the company production yield data reveals more of NTE's struggle to keep consistent production efficiency. The data shows that actual yields often fall short of the 95% target. Seasonal changes in production yield are clear, with higher yields seen in the middle of the year and lower yields at the start and end of the year. These ups and

downs show that there is instability in operations and inefficiencies in keeping a steady output. These findings show important operational inefficiencies that affect production efficiency, profit, and sustainability at NTE. to fix these challenges,

The challenges faced by NTE point to a critical need for an integrated approach that combines lean manufacturing and reliability principles. Such an approach could address the root causes of production inefficiencies, reduce waste, and improve resource utilization. Furthermore, these practices would enhance the company's ability to meet its operational Key Performance Indicators (KPIs) and maintain competitiveness in a rapidly evolving market.

The inefficiencies at NTE have far-reaching implications, affecting not only the company's bottom line but also Ethiopia's economy, as NTE is a major contributor to national revenue, generating over 700 million Birr annually. High production costs due to waste reduce the company's profitability, limiting its capacity to invest in process improvements and employee development. Additionally, addressing these issues presents an opportunity for NTE to set a benchmark for operational excellence in Ethiopia's manufacturing sector. By integrating lean systems and reliability analysis, NTE could achieve substantial improvements in production efficiency, waste reduction, and cost savings, providing a model for other organizations in similar contexts. This research aims to investigate the root causes of production waste at NTE and develop actionable strategies for process optimization. By focusing on the practical application of lean and reliability-centered methodologies, the study contribute to the broader understanding of how these frameworks can be adapted to the unique challenges of Ethiopia's tobacco manufacturing industry.

1.4 Research Questions

The challenges faced by National Tobacco Enterprise (NTE) in the Make-Pack department raise several critical research questions. These questions aim to explore the root causes of excessive production waste, inefficiencies in the manufacturing process, and the potential for improvement through the integration of Lean Systems and Reliability Analysis.

1. What are the potential benefits and challenges of adopting lean systems and RCM practices in improving operational efficiency at NTE?
2. What are the primary causes of production reject at the National Tobacco Enterprise?
3. How can the integration of lean manufacturing principles and reliability-centered maintenance frameworks optimize production processes and reduce material waste at NTE?

1.5 Objectives

1.5.1 General Objective

The general objective of this study is to optimize production waste in the tobacco manufacturing process by integrating Reliability Analysis and Lean Systems, with a specific focus on the Make-Pack department at National Tobacco Enterprise (NTE). This research aims to enhance production efficiency, minimize material waste, and improve overall equipment effectiveness to align with global industry standards.

1.5.2 Specific Objectives

To achieve the general objective, the study focuses on the following specific objectives.

1. To identify the primary causes of production waste in NTE's Make-Pack department and compare them with global industry best practices.
2. To assess the impact of Lean Systems on improving production efficiency and reducing material waste at NTE.
3. To analyze the challenges and potential benefits of integrating Lean Systems and RCM in enhancing operational efficiency at NTE.
4. To evaluate the role of Reliability-Centered Maintenance (RCM) in optimizing equipment performance and minimizing production disruptions.

1.6 Scope

This research aims to optimize production waste and enhance material consumption yield in the Make-Pack Department of the National Tobacco Enterprise (NTE).the study focuses specifically on reducing cigarette rejects and improving the utilization of non-tobacco materials (NTM) to promote efficient resource use and minimize waste.the Make-Pack department is identified as the primary contributor to production waste, making it a crucial area for cost reduction and process improvement.

Inclusion and Exclusion

This study concentrates on analyzing operational inefficiencies, equipment reliability, and material waste in the Make-Pack department using Lean Systems and Reliability-Centered Maintenance (RCM). It excludes upstream processes such as tobacco leaf processing and blending, as well as downstream distribution and sales operations.these exclusions ensure that the research remains focused and manageable within the available timeframe and resources, allowing for a detailed investigation of waste reduction strategies in the targeted department.

Justification for the Scope

The Make-Pack department is selected as the focal point because it directly influences production yield, waste generation, and overall equipment effectiveness. Given the high reject rates and material waste within this department, addressing inefficiencies here is expected to yield significant improvements in cost efficiency and sustainability. Excluding other stages of the production chain helps maintain a sharp research focus, ensuring that the analysis is deep rather than broad. Moreover, applying Lean and RCM principles in this department can provide a scalable model for waste reduction that could be extended to other areas of NTE's operations in future studies.

1.6.1 Limitations of the Study

This study intentionally focused on ensuring a deep and manageable analysis of production waste and operational efficiency within the National Tobacco Enterprise (NTE). The study's scope is strictly confined to the Make-Pack department, which was identified as the primary contributor to cigarette rejects and Non-Tobacco Material (NTM) waste. Consequently, the investigation deliberately excludes upstream processes, such as tobacco leaf processing and blending, as well as downstream operations like product distribution and sales. While the findings are contextualized

within a single case study of NTE, this focused approach allows for a detailed investigation into the complex interactions between Lean systems and reliability failures. The insights and the proposed integrated framework are designed to provide a scalable model that can be adapted and extended to other operational areas within NTE or similar manufacturing environments in future research

1.7 Significance of the Study

The study called "Optimizing Production Waste in the Tobacco Manufacturing Process Using Integrated Reliability Analysis and Lean Systems: A Case Study of National Tobacco Enterprise" is very important for the field of industrial engineering, especially in tobacco industry. From a theoretical view, this research helps to understand how to combine lean manufacturing ideas with reliability analysis to solve problems at National Tobacco Enterprise (NTE). By making a framework that mix these methods, this study add to the knowledge in lean manufacturing and reliability-centered maintenance.the findings help ongoing discussions about how reliability checks can work together with lean ideas for better efficiency in tobacco manufacturing processes. In methodology, this study show a new way that combine lean systems with reliability analysis, especially for the problems at NTE.this framework gives a clear method for looking at and reducing production waste, and it can be a reference for future research and practical use in tobacco industry.the real data from NTE show a way that can be used by other companies with similar problems. Empirically, this research give good insights into how combining lean and reliability analysis works in real-life tobacco manufacturing.the case study of NTE provide useful data and analysis that can help other manufacturers to use similar strategies for better production processes. Also, the findings can help in making decision about improving processes, reducing costs, and making operations more reliable, which is very important for sustainability in manufacturing. From practical side, this research is very useful for manufacturing companies that want to reduce reject rate and improve machine reliability. consultants in the tobacco sector and similar industries can use the framework to make processes better and more sustainable. Also, policymakers and managers can use the findings to create best practices for combining lean and reliability improvements in production systems at NTE and other places.

In summary, this study give both theoretical and practical contributions, making it important for academics, industry professionals, and policymakers who want to make manufacturing processes better in the tobacco industry.

1.8 Organization of the Study

The overall research study consists of six chapters.the first chapter focuses on the introduction and problem identification, incorporating background information, statement of the problem, research aim and objectives, scope, limitations, significance of the study, and organization of the paper.the second chapter presents a comprehensive review of relevant literature on lean manufacturing, reliability analysis, and waste optimization in manufacturing industries. It provides a conceptual understanding of the subject, discusses key theories, models, and previous research findings, and highlights the literature gaps identified.the third chapter addresses the research methodology, detailing the research design, data collection methods, sample size determination, research ethical considerations, data analysis methods, and tools.the fourth chapter focuses on data analysis and results, presenting findings from the case study of National Tobacco Enterprise, including data interpretation and discussion of results in relation to research objectives.the fifth chapter provides a discussion contextualizing the findings within the broader literature, highlighting their implications for theory, methodology, and practice while addressing limitations and potential areas for further research. Finally, the sixth chapter presents the conclusion and recommendations, summarizing key findings, drawing conclusions, and offering actionable recommendations for industry practitioners and policymakers.the study concludes with references and supporting materials.

Chapter Two

Literature Review

2.1 Introduction

Waste optimization is crucial in resource-intensive manufacturing sectors. Regulatory pressures and consumer demands for environmentally friendly products necessitate sustainable practices. Lean Management and Reliability Analysis enhance operational efficiency and reduce waste. Lean Management and Reliability Analysis boost the efficiency of operations and minimise wastes. Lean Manufacturing eradicates non-value-added processes, whereas Reliability Analysis is used to enhance the efficiency of the systems. although the tobacco industry has already researched the systems of lean and reliability analysis, a gap exists. The narrowest scope of research deals with general manufacturing and ignores particular issues in tobacco production (Dewadi et al., 2024).this is why there are no opportunities to reduce waste. The connection of lean and reliability strategies is not examined in many studies. [Khasanah et al. \(2021\)](#) emphasize Reliability-Centered Maintenance (RCM) yet fail to discuss the combination of it with lean practices.

The recent studies describe the issues of waste management, including the inefficiency of operations ([Ali et al., 2019](#); [Awogbemi et al., 2022](#)). Most of the studies fail to integrate lean and reliability analysis, which have the potential to enhance waste management in tobacco.the particular context of tobacco production needs solutions that incorporate both views. ([Gania et al. \(2018\)](#) focus on the alignment of the maintenance activity with the operational objectives, which is commonly neglected in tobacco manufacturing. this review of the literature explores the potential to use lean principles and reliability analysis in tobacco manufacturing.

2.2 Historical Context of Lean Management and Reliability Analysis

Understanding the historical evolution of Lean Management and Reliability Analysis provides context for their convergence in manufacturing.these methodologies share a common origin in efforts to improve efficiency, reduce losses, and enhance effectiveness in response to post-industrial revolution challenges (Ohno, 1988; Womack & Jones, 1997). Lean Management emerged from Japan's post-war automotive sector, focusing on waste elimination. Reliability Analysis originated from safety-critical environments like aerospace and defense. lean evolved into a holistic

philosophy promoting flow, quality, and employee involvement, while Reliability Analysis became a disciplined methodology for optimizing asset performance (Huang et al., 2020). as manufacturing grew more complex, the limitations of applying Lean or Reliability principles in isolation became apparent. Recent decades have seen interest in integrating these approaches to address multidimensional production problems, particularly involving equipment and sustainability (Dewadi et al., 2024; Zhang et al., 2014). despite this convergence, studies exploring their integration within specific sectors, such as tobacco manufacturing, remain sparse.

2.2.1 Origins of Lean Management

Lean Management has its roots in the Toyota Production System (TPS), developed in post-WWII Japan to maximize value by eliminating waste, or "muda (Ohno, 1988).the TPS philosophy emphasized customer-focused production, centered on two main pillars: Just-In-Time (JIT) manufacturing and "Jidoka" (automation with a human touch).these principles aimed to minimize inventory costs, reduce production variation, and ensure each production stage added value. womack and Jones (1997) later formalized Lean thinking, articulating five core principles: defining value, mapping value streams, establishing flow, using pull systems, and striving for perfection. lean's implementation spread rapidly across industries due to its versatility, influencing automotive manufacturing, electronics, pharmaceuticals, and food processing, with the core objective of removing non-value-adding steps while enhancing customer value (Indrawati et al., 2019; Aksar et al., 2022). common tools like Value Stream Mapping (VSM), 5S, and Kaizen were adopted to visualize inefficiencies and drive continuous improvement (Kaneku-Orbegozo et al., 2019). however, in tobacco manufacturing, Lean implementation remains poorly documented, despite its potential for reducing material waste and increasing production efficiency.

2.2.2 Origins of Reliability Analysis in Engineering and Operations

Reliability Analysis originated in high-stakes engineering fields such as aerospace, military, and nuclear energy in the mid-20th century, where system failures posed catastrophic risks. Tools like Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Reliability-Centered Maintenance (RCM) were developed to identify failure causes, evaluate risk, and prioritize preventive action.these techniques evolved into a broader operational management discipline aimed at increasing equipment availability and reducing downtime (Huang et al., 2020). industries

transitioned from reactive to proactive maintenance, Reliability Analysis became central in sectors like pharmaceuticals and steel manufacturing (Geisbush & Ariaratnam, 2023).the rise of predictive maintenance, enabled by digital technologies like IoT sensors and data analytics, further extended reliability tools to real-time monitoring and forecasting of equipment health (Zhang et al., 2014). despite these advances, much literature focuses on high-risk industries, with limited exploration in medium-complexity sectors like tobacco manufacturing, where reliability failures generate costly downtime and quality risks.

2.2.3 Milestones in the Union of Lean and Reliability Principles

The intersection of Lean Management and Reliability Analysis highlights the need for both process efficiency and equipment stability. Originally developed as distinct disciplinesLean focusing on workflow waste and Reliability on technical performancetheir convergence began in the 1990s and 2000s as industries recognized the necessity of synchronizing production flow with equipment uptime (Ali et al., 2019). One of the earliest integrations was incorporating Total Productive Maintenance (TPM) into Lean frameworks, aligning preventive maintenance with Lean's flow-oriented objectives (Sasikumar et al., 2023).recent advances in Industry 4.0 have further reinforced this integration. predictive maintenance strategies using IoT sensors now complement Lean tools like VSM and JIT by ensuring reliable machine operation along coordinated production lines (Zhang et al., 2014). in automotive and electronics manufacturing, studies have shown that combining FMEA with Lean Six Sigma reduces both defects and downtime (Aksar et al., 2022; Han et al., 2021). however, research remains concentrated in high-tech industries, with little attention to legacy or regulated sectors like tobacco.

2.3 Foundational Concepts of Lean Management and Reliability Analysis

Understanding the foundational concepts of Lean Management and Reliability Analysis is essential for exploring how these methodologies function individually and interactively in manufacturing. Both systems aim to enhance operational performance but approach this goal from different yet complementary angles. lean Management emphasizes the elimination of waste and non-value-adding activities in a process, while Reliability Analysis focuses on ensuring the consistent and predictable functioning of equipment and systems (Womack & Jones, 1997; Huang et al.,2020).their integration

is increasingly recognized as critical in modern production environments that must simultaneously manage process efficiency and technical dependability (Geisbush & Ariaratnam, 2023; Dewadi et al., 2024). This section discusses their foundational components, first reviewing Lean's core principles and then turning to the conceptual basis of Reliability Analysis metrics.

2.3.4 Core Principles of Lean Management

At the heart of Lean Management is the pursuit of customer-defined value. Lean aims to eliminate activities that do not contribute directly to this value, known as "muda" or waste (Ohno, 1988). Womack and Jones (1997) outlined five guiding principles of Lean: define value, map the value stream, create flow, establish pull, and pursue perfection. These principles form the foundation for any Lean implementation, regardless of industry. Key tools for implementing Lean principles include Value Stream Mapping (VSM), which visualizes the production process to identify inefficiencies; 5S, which organizes the workplace; Kaizen, which supports continuous improvement; and Just-In-Time (JIT), which aligns production with customer demand to reduce inventory (Indrawati et al., 2019; Aksar et al., 2022). Each tool helps reduce one or more of the seven types of waste identified by the Toyota Production System, such as transportation, motion, waiting, and overproduction.

Lean's success across sectors, from automotive to pharmaceuticals, is due to its adaptability and scalability. For instance, Kaneku-Orbegozo et al. (2019) demonstrated Kaizen's benefits in reducing motion waste in assembly lines, while Dewi et al. (2021) showed how VSM improved lead time efficiency in electronics manufacturing. However, Lean applications in tobacco manufacturing are underrepresented in the literature.

2.3.5 Fundamental Concepts of Reliability Analysis Metrics

Reliability Analysis evaluates a system's ability to perform under specific conditions over time. It involves identifying potential failure modes, quantifying failure rates, and designing maintenance strategies to minimize downtime (Huang et al., 2020). Key tools include Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Reliability-Centered Maintenance (RCM), which focus on mitigating operational risks. Core reliability metrics are Mean Time Between Failures (MTBF), measuring average operational time between failures, and Mean Time To Repair (MTTR), calculating the average time needed to restore functionality. These indicators are essential for evaluating

reliability (Geisbush & Ariaratnam, 2023). Additional tools like Reliability Block Diagrams (RBD) and Root Cause Analysis (RCA) assess system dependencies and trace failure origins (Zhang et al., 2014). Modern Reliability practices integrate with Industry 4.0 technologies such as IoT sensors and data analytics, enabling Predictive Maintenance and real-time condition monitoring, reducing downtime and allowing for proactive interventions in continuous production environments where unscheduled stops are disruptive (Sasikumar et al., 2023).

2.4 Integration of Lean Management and Reliability Analysis

The convergence of Lean Management and Reliability Analysis marks a shift in how manufacturers achieve operational excellence. Lean eliminates inefficiencies, while Reliability Analysis ensures stable equipment performance (Aucasime-Gonzales et al., 2020; Huang et al., 2020). When integrated, these methodologies address process waste and technical failures, which disrupt productivity and quality. Scholars and industry leaders advocate for aligning Lean and Reliability principles to create resilient, cost-effective, and sustainable production systems (Geisbush & Ariaratnam, 2023; Dewadi et al., 2024).

2.4.1 Integration of Lean Management and Reliability Analysis

The integration of Lean Management and Reliability Analysis aims to optimize value delivery. Lean achieves this through process simplification and waste elimination, while Reliability Analysis enhances performance by minimizing breakdowns and maximizing equipment availability (Womack & Jones, 1997; Huang et al., 2020). These disciplines converge on the principle of "stability as a prerequisite for flow," where consistent equipment performance supports Lean's production goals (Ohno, 1988). A foundational framework for integration is Total Productive Maintenance (TPM), which embeds maintenance into production, emphasizing equipment ownership, preventive maintenance, and defect elimination (Sasikumar et al., 2023). Lean Six Sigma combines Lean's speed with Six Sigma's defect reduction, often using reliability tools like FMEA and Root Cause Analysis (Han et al., 2021). These frameworks require adaptation to specific contexts such as tobacco manufacturing, where unique constraints exist (Syahputri et al., 2018).

2.4.2 Methodological Alignment of Lean Management and Reliability Analysis

Methodological alignment between Lean and Reliability occurs through shared tools, data requirements, and performance goals. lean methodologies, such as VSM and 5S, require accurate, real-time data about process performance, which can be enhanced by reliability-based monitoring systems. Similarly, FMEA and RCM rely on operational data that Lean processes often generate through structured workflows (Zhang et al., 2014). A practical example of alignment is the deployment of predictive maintenance strategies alongside JIT production. predictive maintenance ensures machine uptime, supporting Lean's requirement for synchronized, demand-driven production (Geisbush & Ariaratnam, 2023). additionally, digital tools like IoT sensors benefit both disciplines: Lean gains from production flow visualization, while Reliability obtains insights into wear and degradation patterns (Awogbemi et al., 2022). while methodological overlaps exist, few studies provide detailed roadmaps for implementing Lean and Reliability tools together.

2.4.3 Benefits of Integration of Lean Management and Reliability Analysis

The integration of Lean and Reliability principles provides operational, financial, and strategic benefits. Operationally, it enhances production stability by ensuring optimized workflows are supported by reliable equipment (Alrifaey et al., 2020), reducing bottlenecks, unplanned downtime, and rework. For instance, combining JIT with Predictive Maintenance allows firms to meet tight delivery windows without excess inventory (Aksar et al., 2022).

Financially, integrated systems lower maintenance costs by shifting from reactive to proactive strategies while improving labor productivity and material yield (Sasikumar et al., 2023). Strategically, companies that integrate Lean and Reliability can better meet regulatory standards, ensure consistent product quality, and adapt to technological changes. case studies show that companies implementing both disciplines improved Overall Equipment Effectiveness (OEE), reduced defect rates, and shortened lead times (Han et al., 2021; Sulkifli et al., 2022).these improvements enhance customer satisfaction and competitive advantage.

2.5 Waste Types in Manufacturing

Waste in manufacturing encompasses any activity that consumes resources without delivering customer value. Identifying and eliminating such waste is central to Lean Management, which initially defined seven categories of "muda" in the Toyota

Production System (Ohno, 1988).this classification has since expanded to ten waste types, acknowledging previously overlooked inefficiencies such as underutilized talent, energy waste, and environmental impacts (Grewal, 2008; Awogbemi et al., 2022). Systemic forms of waste, including inconsistency (mura), overburden (muri), and hidden inefficiencies, further complicate waste management in modern production systems (Womack & Jones, 1997). Additionally, unreliable equipment and unplanned failures create a waste category often ignored by traditional Lean models, highlighting the lack of sector-specific waste typologies that address the intersection of Lean inefficiencies and reliability-induced disruptions.

The ten recognized waste types in Lean Management include transportation, inventory, motion, waiting, overproduction, over-processing, defects, underutilized talent, energy waste, and environmental waste. Each type negatively impacts operational efficiency, cost structure, and environmental sustainability (Aucasime-Gonzales et al., 2020; Dewi et al., 2021).transportation waste arises from unnecessary movement of materials, particularly evident in tobacco production during the transfer of leaves across processing stages (Fauziah et al., 2022). Inventory waste occurs when excess cured leaves or packaging materials are stockpiled, risking deterioration or obsolescence (Indrawati et al., 2019). Motion waste involves excessive movement by workers, often due to poor layout or unstandardized workstations (Dube & Gupta, 2023). Waiting waste results from machine downtime or unbalanced workflows, frequently observed in curing and packaging stages (Kaneku-Orbegozo et al., 2019). Overproduction leads to surplus output that may not align with market demand, increasing the risk of spoilage in sensitive materials like tobacco leaves (Syahputri et al., 2018). Over-processing entails unnecessary steps, such as redundant inspections or excessive packaging, that do not add customer value (Kholil et al., 2021). Defects include misrolled cigarettes and labeling errors, often requiring costly rework or scrapping (Sasikumar et al., 2023). Underutilized talent manifests when employees' skills and suggestions are not incorporated into process improvements (Azadeh et al., 2017). Energy waste arises from inefficient use of curing ovens or HVAC systems, significantly impacting costs and sustainability (Awogbemi et al., 2022). Finally, environmental waste refers to emissions and non-recyclable byproducts like packaging waste and tobacco dust (Ali et al., 2019).

2.6 Systemic Waste in Manufacturing

Beyond visible forms of muda, systemic inefficiencies rooted in inconsistency (mura), overburden (muri), and hidden waste also impair performance. These three "Ms" complement the original Lean waste types and reflect deeper structural problems in manufacturing (Womack & Jones, 1997).

Mura (Inconsistency) is variation in production processes, schedules, or output quality. In tobacco production, inconsistency in drying times or machine speeds leads to product variability and rework (Dewadi et al., 2024).

Muri (Overburden) results from overloading machines or workers beyond safe or efficient capacity. For example, pushing tobacco cutters to exceed standard throughput rates can cause overheating, breakdowns, and safety hazards (Geisbush & Ariaratnam, 2023). Hidden waste includes subtle inefficiencies such as suboptimal machine settings, small energy leaks, or uncalibrated sensors, which are difficult to detect but cumulatively significant (Zhang et al., 2014).

Systemic waste is harder to visualize using conventional tools like VSM or 5S, yet it underpins many chronic inefficiencies. Addressing these forms of waste requires integrated monitoring systems, consistent standard operating procedures, and a culture of continuous process evaluation.

2.7 Reliability-Induced Waste

Unplanned downtime, frequent minor stoppages, and equipment malfunctions generate a distinct form of waste not traditionally covered in Lean frameworks. Reliability-induced waste emerges when machines fail to perform as expected, resulting in production interruptions, quality defects, and energy inefficiencies (Huang et al., 2020). Predictive maintenance, condition monitoring, and reliability modeling (FMEA and MTBF) are essential to mitigating such losses (Zhang et al., 2014; Han et al., 2021). Despite these challenges, Lean literature rarely addresses failure-induced disruptions unless they directly relate to visible process inefficiencies. Similarly, Reliability literature seldom incorporates Lean waste typologies when discussing the cost of downtime or preventive maintenance schedules.

2.8 Impact of Waste on the Manufacturing Industry

Waste in manufacturing systems exerts wide-ranging effects on performance metrics, operational stability, financial health, and stakeholder trust. As organizations face

increasing pressure to reduce costs, comply with regulations, and meet sustainability expectations, the ability to identify and eliminate waste becomes a strategic imperative. lean Management provides a structured methodology for reducing process inefficiencies, while Reliability Analysis contributes to waste minimization by reducing unplanned downtime and failure-induced disruptions (Womack & Jones, 1997; Huang et al.,2020).

2.8.1 Economic Consequences

One of the direct effects of manufacturing waste is increased operational cost and reduced profit margins. Waste, in the form of defective products, overproduction, or downtime, translates into resource loss, lower productivity, and decreased capacity utilization (Dewi et al., 2021). Inventory waste ties up capital in unsellable stock, while motion and transportation waste increase labor and handling costs without adding value (Aucasime-Gonzales et al., 2020). In tobacco manufacturing, costs escalate when moisture-sensitive leaves spoil due to improper storage or extended curing times. Additional costs arise from rework due to packaging defects or misaligned labels, common in high-speed environments (Syahputri et al., 2018).these wastes also increase utility consumption, especially in curing ovens and climate-controlled storage, contributing to cost inflation and carbon emissions (Awogbemi et al., 2022). While cost analyses are prevalent in Lean Six Sigma literature, they often focus on discrete manufacturing sectors like automotive or electronics (Aksar et al., 2022). Studies in tobacco are scarce and often fail to quantify cost implications across different waste types or connect them to reliability issues like machine breakdowns and maintenance delays.

2.8.2 Operational Disruptions

Operationally, waste introduces variability and unpredictability into production schedules. When machines fail, materials are delayed, or defective products accumulate, production flow is interrupted, and throughput suffers (Geisbush & Ariaratnam, 2023). Waiting time, overburdened workers, and inconsistent material flow disrupt lean systems dependent on precise timing, such as JIT or SMED (Kaneku-Orbegozo et al., 2019). Unplanned downtimes due to dust blockages or temperature fluctuations during curing lead to capacity loss, reducing OEE (Overall Equipment Effectiveness), a key performance indicator for plant efficiency (Sasikumar et al.,

2023). Despite research linking lean waste to schedule disruptions in discrete manufacturing, fewer studies incorporate Reliability Analysis to explain equipment-related schedule failures in continuous operations like tobacco processing.

2.8.3 Quality and Reputational Risks

Waste negatively impacts not just internal metrics but also customer satisfaction and brand perception. Defects, over-processing, and environmental waste compromise quality consistency and compliance, particularly in industries like tobacco, where product integrity is strictly regulated (Ali et al.,2019). For example, improper curing or leaf moisture levels can alter taste, combustibility, and shelf life, while packaging errors may lead to regulatory violations or recalls (Syahputri et al.,2018).

Consumer-facing defects erode trust and can result in lost market share or punitive penalties. in highly regulated sectors, even minor inconsistencies such as incorrect health warnings or misaligned barcodes can lead to product bans or damage public perception. From a Lean perspective, reducing variability and enforcing standardization are key to ensuring consistent output quality (Womack & Jones, 1997). From a Reliability standpoint, minimizing process variability via predictive maintenance and robust design reduces the likelihood of system-induced quality failures (Huang et al.,2020).

2.9 Lean Management and Reliability Analysis Applications in Manufacturing

The practical application of Lean Management and Reliability Analysis across various manufacturing sectors reveals their effectiveness in driving productivity, reducing waste, and improving process stability. while Lean primarily targets process inefficiencies, Reliability Analysis focuses on minimizing the frequency and impact of equipment failures.these two approaches are increasingly being combined to address complex performance challenges that span both production flow and asset integrity (Geisbush & Ariaratnam, 2023; Zhang et al.,2014).

2.9.1 Lean Management Applications

Lean Management has been applied to streamline processes and eliminate waste across various industrial domains. In the automotive industry, Lean principles like Value Stream Mapping (VSM), Just-in-Time (JIT) production, and 5S have significantly reduced lead times and improved inventory turnover (Aksar et al., 2022). In electronics

manufacturing, Lean reduced rework and enhanced component flow by eliminating non-value-added steps (Indrawati et al., 2019). In the tobacco industry, Lean applications have been sporadic but promising. Syahputri et al. (2018) showed that Lean tools reduced packaging defects and minimized leaf spoilage. JIT principles have been piloted in tobacco leaf processing to improve curing efficiency and reduce inventory waste (Awogbemi et al., 2022). However, most tobacco firms apply Lean in isolated areas, typically packaging or logistics, rather than as a systemic production philosophy.

2.9.2 Reliability Analysis Applications

Reliability Analysis has found critical applications in high-risk and capital-intensive industries such as aerospace, nuclear energy, and chemical processing. Tools like Failure Modes and Effects Analysis (FMEA), Reliability-Centered Maintenance (RCM), and predictive maintenance scheduling have significantly reduced downtime and extended equipment lifespan (Han et al., 2021). For example, RCM has been used in pharmaceutical manufacturing to prevent contamination by ensuring HVAC systems function within acceptable ranges (Geisbush & Ariaratnam, 2023).

In tobacco manufacturing, Reliability applications are emerging. Jeon et al. (2020) used FMEA to assess the failure modes in tobacco rolling and cutting machines, identifying critical components that contribute to frequent stoppages. Predictive maintenance using sensor data is also being considered for tobacco curing ovens, where temperature inconsistencies can result in poor product quality (Zhang et al., 2014). However, these efforts often remain project-based and lack a strategic framework for continuous improvement.

2.10 Lean Methodologies in Manufacturing

Lean methodologies are structured tools and practices that operationalize the core principles of Lean Management. These tools aim to eliminate non-value-adding activities, reduce variation, and align production with customer demand. Over the decades, Lean methodologies have evolved to address not only manufacturing waste but also quality, workflow balance, and sustainability concerns (Womack & Jones, 1997). Their practical applications span diverse sectors, from automotive and electronics to healthcare and agriculture. Lean methodologies are typically categorized into three functional domains: process and waste optimization, flow and quality enhancement,

and performance and sustainability measures (Aucasime-Gonzales et al.,2020). while these tools have proven effective across various industries, their adaptation to tobacco manufacturing sector with high variability, tight regulation, and perishable inputs remains limited in the literature.

2.10.1 Waste Reduction and Process Optimization Methodologies

Core to Lean's philosophy is the identification and elimination of waste.tools like Value Stream Mapping (VSM), Just-In-Time (JIT), 5S, and Kaizen are widely recognized for streamlining processes and eliminating inefficiencies (Indrawati et al.,2019; Kaneku-Orbegozo et al.,2019).

- ✚ **VSM** helps visualize material and information flows, enabling identification of bottlenecks and redundant steps. in the Turkish automotive industry, Aksar et al. (2022) demonstrated how VSM reduced lead time and enhanced process flow
- ✚ **JIT** production aligns production schedules with actual demand, minimizing inventory and reducing storage risks. in tobacco leaf processing, JIT could help align curing output with rolling schedules to avoid moisture loss (Dewi et al.,2021).
- ✚ **5S** methodology ensures workplace organization and standardization through five steps: Sort, Set in order, Shine, Standardize, and Sustain.
- ✚ **Kaizen** supports incremental, employee-driven improvement. in Lean culture, empowering workers to suggest operational changes has been shown to reduce waiting and motion waste (Kaneku-Orbegozo et al.,2019).

2.10.2 Production Flow and Quality Enhancement Methodologies

To ensure uninterrupted production and product consistency, Lean offers methodologies that focus on smooth workflow and defect prevention.these include the Kanban System, SMED, Poka-Yoke, and Total Productive Maintenance (TPM) (Womack & Jones, 1997).

- ✚ **Kanban** uses visual cues to signal production needs, preventing overproduction and enabling smooth material movement. in assembly lines, Kanban minimizes inventory and ensures synchronization between stages.
- ✚ **SMED** (Single-Minute Exchange of Die) minimizes changeover times, critical in high-variation environments like tobacco packaging lines. Faster transitions mean less downtime and more flexibility.

- ✚ **Poka-Yoke** refers to mistake-proofing techniques designed to prevent errors at the source. For instance, sensors that detect improper cigarette length or sealing errors prevent defective products from reaching consumers.
- ✚ **TPM** bridges Lean and Reliability by embedding maintenance in daily operations. Operators perform routine checks to prevent breakdowns, thus sustaining Lean flow. [Sasikumar et al. \(2023\)](#) found that TPM integration reduced defect rates and downtime in tire manufacturing.

Although these methodologies are highly effective in quality and flow control, their use in tobacco manufacturing where frequent equipment adjustments are necessary is rarely discussed in academic studies. This research aims to fill that void by evaluating how these methods can stabilize production and ensure product quality in tobacco factories.

2.10.3 Performance Measurement and Sustainability Methodologies

Performance tracking and environmental stewardship are increasingly important in Lean transformations. Andon systems, Lean Six Sigma, Standardized Work, and Industry 4.0 integration represent tools that help monitor, evaluate, and sustain Lean initiatives ([Zhang et al., 2014](#)).

Andon systems use visual indicators to alert operators and supervisors of production issues in real time. This minimizes response times and promotes accountability.

Lean Six Sigma combines the speed of Lean with the statistical rigor of Six Sigma. [Han et al. \(2021\)](#) illustrated its effectiveness in reducing variability and predicting equipment failure in blending operations.

Standardized Work defines the most efficient method to perform a task and ensures consistency across shifts and operators.

Industry 4.0 integration enhances Lean through digital tools like IoT, cloud-based dashboards, and predictive analytics. These technologies enable real-time monitoring of machine conditions and production flows ([Awogbemi et al., 2022](#)).

While performance and sustainability tools are increasingly discussed in modern Lean literature, their adaptation to tobacco's unique operational conditions, curing variability, dust management, and temperature-sensitive workflows is rarely explored. This study contributes by contextualizing these methodologies for improved monitoring and environmental impact control in tobacco production.

2.11 Reliability Analysis Techniques in Manufacturing

In modern manufacturing, reliability analysis is crucial for ensuring that equipment and systems function consistently and efficiently. This is especially important in resource-intensive industries like tobacco manufacturing, where machine failures can lead to significant waste and a decline in product quality. Reliability analysis involves systematic techniques to identify potential failure modes, evaluate their impacts, and develop maintenance and operational strategies (Modarres & Groth, 2023; Kumar et al., 2022). These techniques improve system uptime and contribute to waste reduction, aligning with lean manufacturing goals (Aucasime-Gonzales et al., 2020).

Tools such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Weibull distribution analysis help manufacturers evaluate equipment vulnerabilities and prioritize interventions based on risk. Advancements in predictive maintenance, driven by Industry 4.0 technologies, enable data-driven approaches like Remaining Useful Life (RUL) forecasting and condition monitoring to predict breakdowns (Er-Ratby et al., 2024; Han et al., 2021). These innovations represent a shift from reactive to preventive reliability strategies. While reliability techniques are widely used in aerospace and automotive sectors, their application in the tobacco industry is limited. Unique challenges, such as high dust exposure and compliance with stringent product consistency standards, require customized reliability approaches (Latinovic et al., 2020; Ali et al., 2019).

2.11.1 Failure Analysis and Predictive Techniques

Reliability in manufacturing relies heavily on techniques that can detect, analyze, and predict failures before they lead to significant operational disruptions. Failure analysis and predictive techniques offer structured methods for identifying potential failure modes, evaluating their consequences, and implementing preventive actions to maintain process continuity and minimize waste. In tobacco manufacturing, where equipment must operate under unique stressors like dust accumulation and humidity fluctuations, these tools are crucial for reducing downtime, ensuring product quality, and improving overall system efficiency (Han et al., 2021; Latinovic et al., 2020). This section explores four primary techniques: Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Weibull Analysis, and Accelerated Life Testing (ALT), emphasizing their relevance and potential application in the tobacco industry.

Failure Modes and Effects Analysis (FMEA)

FMEA is a systematic approach for identifying possible failure modes within a system and analyzing their effects on operational performance and safety. It prioritizes risks based on severity, occurrence, and detection, using a calculated Risk Priority Number (RPN) to guide corrective actions (Jeon et al.,2020). in tobacco production, FMEA can be applied to critical processes such as cigarette rolling or curing oven operation, where minor malfunctions such as uneven temperature or tobacco dust buildup can cause major product losses or equipment damage (Huang et al.,2020). Han et al. (2021) further expand the utility of FMEA by incorporating predictive elements like Remaining Useful Life (RUL) estimations, allowing for maintenance scheduling based on data trends rather than reactive responses.

✚ Fault Tree Analysis (FTA)

FTA complements FMEA by providing a visual representation of the logical relationships among system failures. It helps engineers trace back from a top-level system failure to root causes, using Boolean logic to map potential event paths. this method is particularly useful in diagnosing rare but high-impact failures, such as curing system shutdowns or emissions control system malfunctions in tobacco manufacturing (Kumar et al.,2022). By quantifying the likelihood of each event path, FTA supports more informed risk mitigation strategies.

✚ Weibull Analysis for Failure Prediction

Weibull analysis is a statistical technique used to model time-to-failure data and assess the reliability life cycle of components. It helps determine failure distributions whether early, random, or wear-out phase and predict failure probabilities under different usage conditions (Modarres & Groth, 2023). in tobacco manufacturing, Weibull analysis can assist in evaluating the life expectancy of parts exposed to corrosive tobacco dust, such as rollers and conveyors, allowing for optimized replacement cycles and minimized downtime.

✚ Accelerated Life Testing (ALT)

ALT involves subjecting components to elevated stress conditions (temperature, vibration, or humidity) to simulate aging and identify failure mechanisms in a compressed timeframe. this technique is particularly relevant in developing or testing new machinery used in the tobacco sector, such as automated cutting devices or packaging equipment, which may degrade rapidly in real-world conditions (Alrifaiy et

al.,2020). ALT helps manufacturers design more durable systems and refine maintenance protocols based on empirical degradation data.

2.11.2 Maintenance and Reliability Improvement Methods

In tobacco manufacturing, system reliability is not only for efficiency but also to meet strict regulation and keep product quality consistent. Reliability improvement combine different methods to extend equipment life, raise availability, and reduce downtime, which directly lower waste and save resources. Reliability-Centered Maintenance (RCM) gives a structured way to plan maintenance by finding system functions, failure modes, and setting priority based on risk and safety, helping focus resources on critical parts without unnecessary work (Alrifayy et al., 2020; Khasanah et al., 2021). Total Productive Maintenance (TPM) bring maintenance into daily operations by training operators to do small checks and fixes, stopping common problems like roller misalignment or dust blockages before they cause breakdown, and when combined with RCM, create a strong reliability framework that can raise uptime up to 15% (Sulkifli et al., 2022; Geisbush & Ariaratnam, 2023). Predictive maintenance adds data-driven monitoring using sensors and condition analysis to forecast failures based on actual machine health, allowing timely action and avoiding waste or compliance issues in processes like cigarette rolling or curing chambers (Han et al., 2021; Er-Ratby et al., 2024; Latinovic et al., 2020). Finally, Failure Reporting, Analysis, and Corrective Action Systems (FRACAS) close the loop by recording failures, doing root cause analysis, and confirming corrective action, building long-term knowledge and preventing repeat issues such as moisture variation or packaging faults, especially when combined with lean tools like Kaizen (Modarres & Groth, 2023). Together, these methods form a complete reliability strategy that support continuous improvement, reduce production waste, and ensure compliance in a regulated industry like tobacco manufacturing.

2.11.3 Performance Measurement and System Optimization

In reliability-focused manufacturing, measurement is essential to improvement. without quantifiable data, efforts to enhance system performance and minimize failures become speculative and often ineffective. performance measurement in reliability engineering provides a factual basis for decision-making and allows manufacturers to assess system health, track downtime trends, and evaluate the effectiveness of maintenance strategies.

in industries like tobacco manufacturing where precision, uptime, and compliance are vital using the right performance metrics and optimization tools is key to reducing waste and sustaining productivity. This section explores three important concepts in performance measurement and system optimization: Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and Reliability Block Diagrams (RBD), concluding with the role of Root Cause Analysis (RCA) in identifying and eliminating the sources of inefficiencies.

Mean Time Between Failures (MTBF)

MTBF is a statistical measure used to evaluate the average time between equipment failures under normal operating conditions. It provides insight into the inherent reliability of a system or component and is commonly used to set maintenance schedules and performance targets (Khasanah et al., 2021). A high MTBF indicates reliable equipment that fails infrequently, while a low MTBF suggests that more frequent maintenance or design changes may be required. In tobacco production, machines like leaf cutting or cigarette rolling equipment often operate under stress from dust and humidity. Monitoring MTBF in such cases allows maintenance teams to predict when breakdowns are likely and intervene proactively. Doostparast et al. (2014) emphasize the use of MTBF in preventive maintenance planning and optimizing maintenance intervals to increase availability.

Mean Time to Repair (MTTR)

MTTR measures the average time required to repair a failed component or system and restore it to full operation. It reflects the efficiency of the maintenance process and impacts total equipment availability. A lower MTTR not only reduces production downtime but also limits product losses during machine recovery periods. MTTR serves as a key indicator of responsiveness and process resilience. Combining MTBF and MTTR allows manufacturers to calculate overall system availability and set realistic uptime targets. According to Khasanah et al. (2021), reducing MTTR through operator training, spare parts management, and simplified diagnostics directly improves operational efficiency.

Reliability Block Diagrams (RBD)

Reliability Block Diagrams are graphical models that represent the functional interdependencies between components in a system. They are used to calculate system reliability based on component reliability and configuration—series, parallel, or hybrid.

RBDs help identify critical points of failure and explore how redundancies or reconfigurations might improve overall performance (Modarres & Groth, 2023). By visualizing dependencies and bottlenecks, RBDs support design improvements and maintenance prioritization. Kumar et al. (2022) argue that RBDs are especially useful in planning system upgrades or evaluating the impact of new technologies on existing reliability structures.

Root Cause Analysis (RCA)

Root Cause Analysis is a structured method used to identify the underlying causes of system failures. Rather than treating symptoms, RCA seeks to eliminate the root problems that lead to recurring issues. It is often conducted after a failure event and includes data collection, fault tree generation, causal analysis, and implementation of corrective actions. In manufacturing environments, RCA supports continuous improvement and strengthens preventive maintenance programs. Endo and Hozumi (2021) emphasize the value of RCA in machining operations, where recurring tool wear or material inconsistencies often result in quality defects. In the tobacco sector, RCA can be applied to address chronic issues like packaging inconsistencies, rolling machine jams, or curing irregularities, which frequently lead to waste. Alrifayeh et al. (2020) note that integrating RCA into broader RCM frameworks amplifies its impact, allowing insights from RCA to inform maintenance planning and reliability modeling.

2.12 Limitations of Lean Management and Reliability Analysis without Integration

Lean Management and Reliability Analysis are established methodologies aimed at enhancing efficiency and minimizing waste in manufacturing. Lean focuses on eliminating non-value-adding activities through tools like Just-In-Time (JIT), 5S, and Value Stream Mapping (VSM), whereas Reliability Analysis aims to improve system uptime using methods such as Failure Mode and Effect Analysis (FMEA) and Reliability-Centered Maintenance (RCM) (Aucasime-Gonzales et al., 2020; Khasanah et al., 2021). However, applying these approaches in isolation can lead to significant limitations, including fragmented decision-making and inconsistent improvement initiatives. This is particularly critical in industries like tobacco manufacturing, where production efficiency is closely tied to process performance and equipment reliability (Dewadi et al., 2024; Latinovic et al., 2020). Without integration, waste reduction efforts may overlook causes like unplanned equipment downtime, and maintenance activities

can disrupt lean flows. consequently, the lack of synergy between lean and reliability often results in misaligned goals, redundant efforts, and suboptimal outcomes. the following sections will delve into these limitations, starting with the challenges of siloed implementation.

2.12.1 Isolated Approaches Hindering Efficiency

When lean Management and Reliability Analysis operate separately, they create operational silos with different agendas and metrics, leading to redundant activities and conflicting priorities that hurt system performance. lean teams focus on process flow and inventory, while maintenance teams pursue equipment availability without considering production impacts (Geisbush & Ariaratnam, 2023). this disconnect can cause clashes between initiatives like Kaizen and maintenance schedules, resulting in disruptions (Azadeh et al., 2017; Kaneku-Orbegozo et al., 2019). Isolated approaches obscure inefficiencies, as lean teams may misidentify bottlenecks, ignoring machine breakdowns, while maintenance focuses on metrics like Mean Time Between Failures (MTBF) without addressing the effect of downtime on efficiency (Huang et al., 2020; Han et al., 2021). In tobacco manufacturing, this fragmentation poses risks due to strict environmental controls, where equipment failures can lead to spoilage and regulatory non-compliance if reliability risks are ignored (Latinovic et al., 2020). Cultural differences also complicate integration, as lean and Reliability functions often have different leadership and priorities, making collaboration hard; successful integration needs a unified vision and cross-disciplinary leadership (Smart et al., 2003).

2.12.2 Scalability Challenges in Complex Production Systems

As production get more dynamic, scalable improvement is very important. Lean management and reliability analysis help improve operation, but using them alone can cause problem in complex systems. Lean focus on process flow and waste reduction, while reliability focus on uptime and maintenance. If they not work together, scaling is hard, especially in tobacco industry with regulation and changing demand (Dewadi et al., 2024; Ali et al., 2019). Standalone lean need stable conditions, like JIT or VSM, and become fragile when raw materials vary or equipment age. Without predictive maintenance, lean can face disruption (Han et al., 2021; Latinovic et al., 2020). Reliability tools like FMEA look at machines only, not full workflow, so assets may be good but system still fail to meet throughput (Doostparast et al., 2014). In tobacco, processes like leaf curing and packaging depend on each other, so lean without

reliability may increase defect when batch size reduce (Latinovic et al., 2020).

Industry 4.0 add more challenge. IoT and AI need frameworks to handle real-time data from process and equipment (Bona et al., 2021; Cagnetti et al., 2021). Lean alone cannot predict all issues, reliability alone miss production flow. Also, lean and reliability usually in different department with separate goal, making coordination hard (Smart et al., 2003).

To solve this, integrated framework is needed that combine lean and reliability. TPM with lean tools like 5S align maintenance and process improvement (Sulkifli et al., 2022). Simulation with VSM allow checking how demand and machine reliability affect performance. Using reliability data in such approach help make decisions that scale and keep system efficient.

2.13 Optimizing Waste and Enhancing Operational Efficiency Case Studies

optimizing waste and enhancing operational efficiency are crucial in manufacturing, significantly influenced by methodologies like lean management and reliability-centered maintenance (RCM). studies by Dinesh et al. (2022) and Han et al. (2021) show substantial improvements across sectors, including automotive, steel, and tobacco. in process manufacturing, waste is embedded in material flows, energy usage, and environmental controls, necessitating real-time monitoring and strict quality adherence. a key strategy is value stream mapping (VSM) to visualize and streamline flows (Dewadi et al., 2024). for example, Sulkifli et al. (2022) applied total productive maintenance (TPM) with VSM in sugar production, achieving a 20% downtime reduction. in tobacco, Latinovic et al. (2020) introduced an adaptive intelligence system using Industry 4.0 tools to predict spoilage during leaf curing, optimizing environmental control and reducing waste. additionally, Don et al. (2016) explored recycling in tobacco, revealing that waste from production can be reintegrated, suggesting that regulatory concerns can drive waste optimization beyond cost considerations. in discrete manufacturing, such as automotive and electronics, assembly processes often experience waste from motion, defects, and waiting time. lean strategies like just-in-time (JIT), 5S, and Kaizen have been effective in waste reduction. for instance, Dinesh et al. (2022) applied VSM in carton production, reducing work-in-process inventory by 15%. Indrawati et al. (2019) documented significant waste reductions in a steel plant through layout redesign. while waste is visible in these

environments, an overreliance on surface metrics can be misleading. studies by [Sasikumar et al. \(2023\)](#) and [Gomaa \(2023\)](#) show how integrating lean six sigma methodologies enhances quality control. predictive maintenance schedules using remaining useful life (RUL) data help avoid costly machine failures, as demonstrated by [Han et al. \(2021\)](#), who improved maintenance timing and reduced downtime in multi-state systems. however, the integration of lean and reliability strategies is often insufficient, leading to missed optimization opportunities. in the tobacco sector, strict regulations and material perishability present challenges. lean techniques have been underutilized; [Dewadi et al. \(2024\)](#) applied VSM and JIT in tobacco production, identifying overproduction and excessive handling as waste sources. [Syahputri et al. \(2018\)](#) showed lean six sigma techniques reduced defect rates in cigarette paper production by 12%, suggesting that lean tools can improve compliance outcomes. however, improvements are often undermined by equipment breakdowns without reliability support. [Latinovic et al. \(2020\)](#) highlighted predictive analytics to mitigate equipment-related waste in tobacco production. despite recycling initiatives ([Don et al., 2016](#)) reducing environmental waste, many tobacco case studies reveal a lack of integration between lean and reliability approaches. a unified framework balancing lean flow optimization with predictive reliability strategies is lacking, highlighting a critical gap. improving efficiency requires a motivated, informed workforce aligned with organizational goals. lean philosophies emphasize employee engagement through Kaizen, essential for success. [Kaneku-Orbegozo et al. \(2019\)](#) documented a Peruvian case where worker suggestions led to over 10% efficiency improvements. [Azadeh et al. \(2017\)](#) combined resilience engineering with lean strategies, showing that employee involvement enhances system performance. these findings underscore the importance of fostering a culture of adaptability, particularly in industries like tobacco, where environmental and regulatory variability is high.

2.14 Models and Frameworks of Lean Management and Reliability Analysis

In modern manufacturing, the pursuit of operational excellence requires a solid understanding of lean management principles and reliability analysis frameworks. both aim to minimize inefficiencies: lean focuses on reducing process waste, while reliability analysis ensures system dependability. when integrated effectively, these approaches yield synergistic outcomes that enhance productivity and sustainability. lean

management identifies and eliminates non-value-adding activities, aligning with reliability analysis's goal of ensuring equipment uptime and process consistency (Aucasime-Gonzales et al., 2020; Geisbush & Ariaratnam, 2023). lean principles, originating from the Toyota Production System, emphasize continuous improvement and customer-centric value, whereas reliability analysis stems from engineering, focusing on system performance under specific conditions. this convergence is crucial in resource-intensive sectors like tobacco manufacturing, where waste appears in forms such as material, time, motion, and energy, and equipment failures can disrupt production flow. despite their effectiveness in industries like automotive and aerospace, their combined application in tobacco manufacturing remains underexplored (Dewadi et al., 2024).

2.14.1 Foundational Lean Models

lean management is supported by core models and tools that provide structured methodologies for waste reduction and value maximization. key among these are Value Stream Mapping (VSM), the 5S methodology, Kaizen, Kanban, and the DMAIC framework.

- ✚ **Value Stream Mapping (VSM)** is a visual tool that analyzes and improves the flow of materials and information in production systems. it helps organizations identify non-value-added activities, streamline workflows, and reduce lead times (Aksar et al., 2022; Dewadi et al., 2024). in tobacco manufacturing, VSM can map leaf curing, rolling, and packaging stages, enabling managers to locate inefficiencies and implement targeted improvements.
- ✚ **The 5S Methodology** Sort, Set in Order, Shine, Standardize, and Sustain drives workplace organization and cleanliness. Indrawati et al. (2019) demonstrate that 5S increases productivity by optimizing workspaces and minimizing disruptions.
- ✚ **Kaizen**, or continuous improvement, encourages employee-led incremental changes to enhance processes. Sujata Dutta (2024) highlights the importance of worker participation in sustaining operational improvements, particularly relevant in tobacco production, where manual oversight of curing and blending is crucial.
- ✚ **Kanban** is a pull-based system that aligns production with actual customer demand, reducing inventory and preventing overproduction. Kumar et al. (2022) illustrate how visual scheduling tools in Kanban foster agility in response to market changes.
- ✚ **DMAIC** (Define, Measure, Analyze, Improve, Control) is a data-driven

improvement cycle from Six Sigma that helps organizations diagnose process deficiencies, implement corrective actions, and sustain improvements (Jilcha Sileyew, 2021).

these lean models collectively support a structured approach to waste reduction and process optimization. however, successful implementation relies on cultural alignment, employee training, and leadership commitment (Grewal, 2008).

2.14.2 Key Reliability Frameworks

Reliability frameworks ensure system dependability by predicting, preventing, and mitigating equipment failures. in high-throughput sectors like tobacco manufacturing, reliability is paramount to maintaining continuous operations and product quality. core tools include Reliability Block Diagrams (RBD), Failure Mode and Effects Analysis (FMEA), Total Productive Maintenance (TPM), and Predictive Maintenance systems. Reliability Block Diagrams (RBD) visually represent how system components affect overall performance. By modeling different configurations series, parallel, or hybrid RBDs help identify bottlenecks and failure-prone areas (Khasanah et al., 2021). Failure Mode and Effects Analysis (FMEA) is a proactive risk assessment tool that evaluates potential failure modes, their effects, and mitigation priorities. Kumar et al. (2022) affirm FMEA's utility in prioritizing maintenance actions and improving safety. Total Productive Maintenance (TPM) involves all employees in maintaining equipment performance. Mohamed Er-ratby et al. (2024) highlight TPM's role in reducing unplanned downtime and fostering a reliability-focused culture, which is vital in preventing spoilage during the tobacco curing process.

Predictive Maintenance, empowered by Industry 4.0 technologies, uses data analytics to forecast equipment failures. Hasan et al. (2023) demonstrate its effectiveness in minimizing disruptions, particularly in dynamic and dust-prone environments like tobacco factories, together these frameworks offer comprehensive strategies to bolster equipment reliability. However, their application in the tobacco sector requires adaptation to address unique challenges such as high humidity, dust management, and regulatory compliance (Latinovic et al., 2020).

2.14.3 Integration Frameworks

The integration of lean and reliability models presents a promising frontier in production optimization. while lean targets process waste, reliability ensures equipment functionality when combined, they reinforce each other to enhance operational

resilience. [Smart et al. \(2003\)](#) advocate for this synergy, describing it as a union of efficiency and robustness. For instance, integrating VSM with reliability metrics like MTBF can reveal how equipment downtimes disrupt value streams, enabling more effective countermeasures. Similarly, aligning TPM with Kaizen encourages proactive maintenance guided by frontline observations, fostering both efficiency and system uptime.

Emerging integration frameworks explore the convergence of these paradigms. [Harikannan et al. \(2023\)](#) suggest that combining lean tools (5S, VSM) with predictive reliability approaches (FMEA, RUL estimation) leads to more adaptive and responsive manufacturing systems. However, most studies lack context-specific applications particularly in regulated industries like tobacco manufacturing. Thus, while the theoretical basis for integration is strong, empirical validation remains limited. Addressing this gap requires developing industry-specific hybrid models that align with operational, regulatory, and sustainability goals.

2.15 Strategies and Measures for Optimizing Waste and Enhancing Operational Efficiency

In an era marked by increased global competition, environmental scrutiny, and volatile consumer demand, manufacturing organizations are compelled to adopt multifaceted strategies to remain efficient and sustainable. The intersection of lean manufacturing and reliability analysis provides a comprehensive framework for operational enhancement, where lean principles target the elimination of process inefficiencies and reliability measures focus on maximizing equipment uptime. Together, they offer a dual lens through which waste can be minimized, and performance can be maximized. Lean implementation strategies such as Value Stream Mapping (VSM), Just-In-Time (JIT), and employee-driven Kaizen initiatives, along with reliability tools like predictive maintenance and Reliability-Centered Maintenance (RCM), form the core of transformative manufacturing practices. Evidence from case studies across various sectors, including automotive, steel, and increasingly in tobacco manufacturing, underscores the effectiveness of these strategies when adapted contextually. However, success hinges not only on the selection of methodologies but also on how they are integrated, institutionalized, and evaluated.

2.15.1 Lean Implementation Strategies

Value Stream Mapping (VSM) is a key visual management tool for spotting waste and

inefficiencies in production workflows. It maps the material and information flow from start to finish of a process, helping practitioners find bottlenecks, excess inventory, waiting times, and overprocessing. [Aksar et al. \(2022\)](#) report a successful use of VSM in the Turkish automotive industry, where its combination with simulation modeling cut lead times and improved throughput. In tobacco manufacturing, VSM can be adapted to analyze the curing and rolling processes to find delays from humidity or leaf handling inefficiencies. Just-In-Time (JIT) Production aligns production volumes with actual customer demand, minimizing inventory levels and associated waste. [Dewadi et al. \(2024\)](#) highlight its relevance in preventing spoilage in tobacco due to high humidity. Similarly, [Indrawati et al. \(2019\)](#) confirm a 15% inventory waste reduction in steel manufacturing through synchronized production scheduling, showing JITs cross-sector applicability. Kaizen, which emphasizes continuous, small improvements led by employees, builds a culture of accountability and innovation. Studies like [Kaneku-Orbegozo et al. \(2019\)](#) show that Kaizen-driven changes by frontline workers lead to measurable efficiency gains. For example, in tobacco production, Kaizen initiatives could involve adjustments to curing oven schedules or improving ergonomic designs during leaf sorting to reduce fatigue and errors. Employee engagement is another key element. According to [Grewal \(2008\)](#), successful lean transformation relies heavily on worker participation, leadership support, and reskilling efforts. [Hossain and Purdy \(2023\)](#) stress the role of continuous training in helping lean transitions, especially where new technologies or cultural changes are introduced. Kanban and DMAIC are also important parts of lean strategies. Kanban systems regulate production through visual signals, ensuring material flow matches demand. [Kumar et al. \(2022\)](#) show its effectiveness in managing resource-intensive production environments. DMAIC (Define, Measure, Analyze, Improve, Control) offers a structured way to identify, quantify, and solve process inefficiencies, ensuring lasting results ([Jilcha Sileyew, 2021](#)).

2.15.2 Reliability Improvement Measures

Predictive Maintenance has revolutionized equipment management by leveraging real-time data and analytics to forecast failures. [Er-Ratby et al. \(2024\)](#) and [Latinovic et al. \(2020\)](#) provide evidence of how predictive maintenance improves productivity by addressing equipment failure proactively. In tobacco factories, where dust accumulation can degrade equipment, predictive models using sensor data can preemptively trigger

maintenance before critical breakdowns occur.

Reliability-Centered Maintenance (RCM) prioritizes maintenance tasks based on their impact on system reliability. [Khasanah et al. \(2021\)](#) and [Geisbush & Ariaratnam \(2023\)](#) note that RCM enhances system availability and performance, particularly in process-intensive industries. The hybrid models proposed by [Alrifayy et al. \(2020\)](#) integrate cost and reliability data, creating optimal maintenance schedules. Though originally applied to gas turbines, these principles are adaptable to tobacco manufacturing's curing ovens and air filtration systems.

Root Cause Analysis (RCA) and Failure Mode and Effects Analysis (FMEA) support reliability by systematically identifying failure points and implementing corrective measures. [Endo and Hozumi \(2021\)](#) show that RCA effectively pinpoints underlying causes of defects in machining operations, a concept easily translatable to tobacco leaf processing.

Simulation Modeling, as applied by [Aksar et al. \(2022\)](#), enhances process design by allowing hypothetical interventions before real-world implementation. In tandem with lean tools, simulation enables comprehensive system optimization, including downtime reduction and throughput enhancement.

2.16 Measurement and Evaluation Tools of Industry Performance

Effective performance measurement is indispensable to sustaining lean manufacturing and reliability improvement initiatives in modern manufacturing systems. Without structured metrics and evaluation frameworks, organizations cannot accurately assess operational effectiveness, diagnose inefficiencies, or track progress over time. In industries such as tobacco manufacturing where compliance, precision, and quality are paramount the role of performance evaluation becomes even more critical. Lean and reliability strategies rely heavily on quantifiable indicators such as lead time, defect rates, equipment uptime, and inventory turnover, all of which are essential for benchmarking and continuous improvement. According to [Aksar et al. \(2022\)](#), tools like Value Stream Mapping (VSM) enable organizations to visualize and quantify waste within their processes, offering a foundational step for performance enhancement. Similarly, [Khasanah et al. \(2021\)](#) emphasize that reliability metrics, particularly Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), provide crucial insights into equipment efficiency and maintenance efficacy. Furthermore, comprehensive indices such as Overall Equipment Effectiveness (OEE) have proven

effective in consolidating availability, performance, and quality into a single, actionable metric (Cheah et al.,2020).the integration of both qualitative and quantitative assessment methods is essential, as highlighted by Indrawati et al. (2019), who argue that the inclusion of human factors and contextual feedback enriches data-driven evaluations.therefore, a robust and industry-sensitive measurement framework not only supports effective decision-making but also facilitates the long-term success of lean and reliability programs.

2.16.1 Key Performance Indicators

Key performance indicators (KPIs) provide quantifiable benchmarks for assessing the effectiveness of lean and reliability initiatives.these metrics offer insights into production flow, resource utilization, maintenance efficiency, and compliance alignment. For lean systems, common KPIs include lead time, work-in-progress (WIP) inventory, throughput, defect rates, and transportation efficiency. in reliability contexts, metrics such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), Remaining Useful Life (RUL), and system availability are used.

Aksar et al. (2022) and Dinesh et al. (2022) show that Value Stream Mapping (VSM) leads to significant improvements in lead time and inventory levels in the automotive and carton manufacturing sectors, with reported 20% and 15% reductions respectively. applied to tobacco, these KPIs can track moisture-related spoilage in the curing phase or identify delays in the rolling and packaging lines due to machine downtime.

Reliability-centered KPIs are equally critical. Khasanah et al. (2021) demonstrated how MTBF and MTTR can be used to boost uptime by 15% in process industries. For example, in tobacco production, MTBF can indicate the performance of curing ovens, while MTTR can help track the responsiveness of maintenance teams to dust-induced equipment failures. Overall Equipment Effectiveness (OEE) is another comprehensive KPI integrating availability, performance, and quality. cheah et al. (2020) and Garcia-Garcia et al. (2022) applied OEE in semiconductor and food sectors to measure productivity and changeover effectiveness. in tobacco factories, OEE can track packaging line efficiency, adjusting for humidity and particulate challenges that impact machine uptime and output quality.

2.16.2 Evaluation Methods

A robust evaluation framework often combines both qualitative and quantitative methods. while quantitative metrics offer precision, qualitative insights are invaluable

for interpreting behavioral, procedural, and cultural impacts of lean and reliability implementations.

For instance, [Indrawati et al. \(2019\)](#) applied a mixed-method approach to evaluate lean practices in a steel facility, combining numerical KPIs with employee feedback. Similarly, [Kaneku-Orbegozo et al. \(2019\)](#) assessed Kaizen effectiveness by integrating operator perspectives with production data. In tobacco manufacturing, this dual approach is beneficial: quantitative indicators can assess curing oven performance, while qualitative interviews may reveal gaps in operator training or resistance to TPM protocols.

[Gomaa \(2023\)](#) supports the use of mixed-methods in Lean Six Sigma evaluations, emphasizing its suitability in identifying both operational and human-factors-based success barriers. This triangulated approach is particularly useful in tobacco production, where environmental constraints, regulatory mandates, and workforce variability intersect.

2.16.3 Tools for Measuring Effectiveness

Several tools are commonly used to structure and support performance evaluation. These include:

Value Stream Mapping (VSM): Not only a diagnostic tool, but also an effective means of tracking performance improvement. [Aksar et al. \(2022\)](#) and [Dinesh et al. \(2022\)](#) show that VSM offers a baseline for lead time and WIP metrics, which can then be reassessed post-intervention.

Overall Equipment Effectiveness (OEE): As applied by [Cheah et al. \(2020\)](#), OEE helps assess machine availability, performance, and output quality in a single framework. For tobacco plants, this tool can track the performance of moisture-sensitive equipment like dryers and packagers.

Reliability-Centered Maintenance (RCM) Tools: Using MTBF and MTTR as core indicators, these tools assess the effectiveness of maintenance planning. [Khasanah et al. \(2021\)](#) show their successful use in plant availability improvement.

DMAIC (Define, Measure, Analyze, Improve, Control): As used by [Kholil et al. \(2021\)](#), DMAIC enables structured root-cause analysis and provides a mechanism for measuring and sustaining gains. In tobacco, this could apply to quality control for rolling and labeling processes.

FMEA and RUL Simulations: [Han et al. \(2021\)](#) and [Jeon et al. \(2020\)](#) used these tools

to forecast equipment reliability. in tobacco production, these can optimize machine servicing intervals, thus reducing unplanned downtime

2.17 Conceptual Framework

In today's manufacturing environment, optimizing production waste is key for improving operational efficiency and sustainability. This framework combines lean Management principles and Reliability Analysis, both crucial for minimizing waste across production processes. Lean manufacturing emphasizes maximizing value while minimizing waste through tools like Value Stream Mapping (VSM), Just-In-Time (JIT) production, continuous improvement (Kaizen), and the 5S methodology. These methods aim to identify and remove non-value-adding activities, streamlining processes and boosting productivity. VSM visualizes workflows, pinpointing inefficiencies and addressing wasteful practices. Reliability analysis focuses on methods like Reliability-Centered Maintenance (RCM), Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), and Root Cause Analysis (RCA), which are essential for ensuring equipment reliability and maintaining optimal performance. By preventing equipment failures and reducing downtime, organizations can cut rework and defects, critical forms of waste that impact efficiency.

The dependent variable in this framework is optimized production waste levels, meaning minimal waste across all production areas, including material waste, energy use, and downtime. Lean manufacturing directly helps reduce waste by streamlining processes, while reliability analysis boosts performance by minimizing breakdowns and maximizing equipment availability (Womack & Jones, 1997; Huang et al., 2020). The integration of these methods creates a synergistic effect that amplifies their benefits. Insights from reliability analysis can inform lean initiatives by finding waste linked to unreliable equipment, while lean principles can enhance maintenance processes, known as lean maintenance. This relationship encourages continuous improvement and supports emerging concepts like lean Six Sigma, which combines waste reduction with defect reduction.

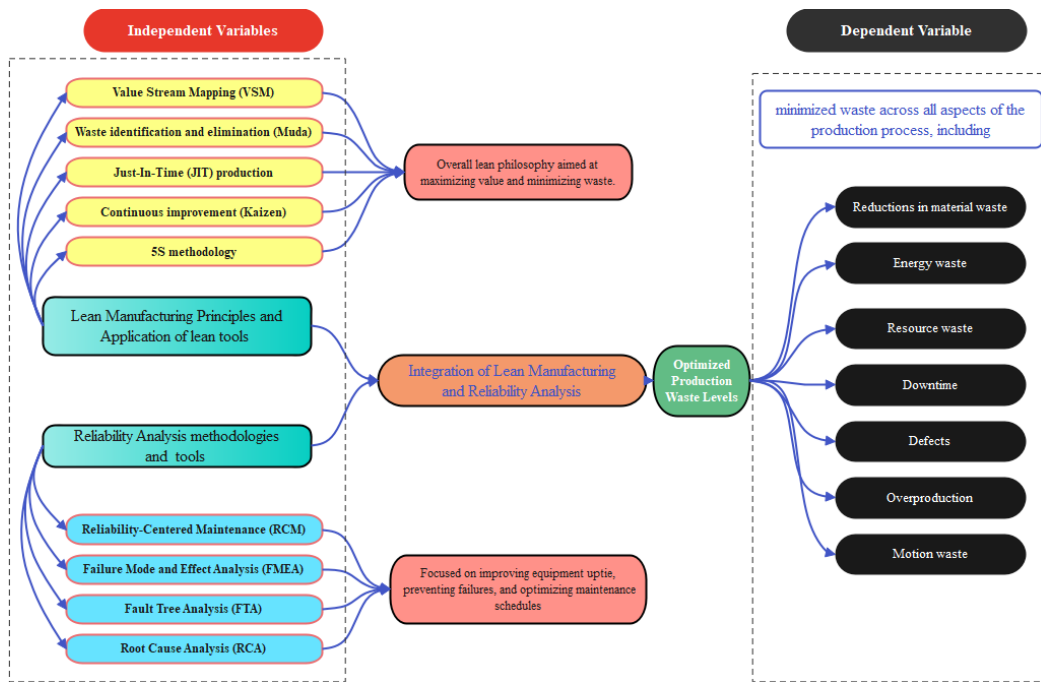


Figure 2.1 Conceptual Framework (Source: own work)

This conceptual framework gives manufacturing organizations a structured approach to effectively identify and address waste. It guides the selection and implementation of lean tools like VSM and reliability techniques such as RCM and FMEA, stressing the importance of integrating these efforts for comprehensive waste reduction. Contextual factors, including technology and organizational culture, are also highlighted as vital for successful waste optimization initiatives. Organizations can use advanced data analytics to find waste patterns and implement targeted interventions that align with lean and reliability principles. The framework serves as a foundation for developing methodologies and metrics to measure the impact of waste reduction efforts, enabling organizations to track progress and refine strategies. The literature shows the importance of combining lean and reliability principles for optimizing production waste, especially in industries like tobacco, automotive, and pharmaceuticals. Studies by Aksar et al. (2022) and Dinesh et al. (2022) demonstrate VSMs effectiveness in waste reduction, while Alrifayy et al. (2020) and Geisbush and Ariaratnam (2023) discuss RCMs role in improving operational reliability. The application of lean manufacturing's focus on waste elimination, as defined by Aucasime-Gonzales et al. (2020), is complemented by insights from Smart et al. (2003), exploring the synergy between lean and high reliability thinking. This integration framework provides a clear method for addressing production waste and emphasizes ongoing refinement in response to changing industry

challenges.

2.18 Summary of the Literature

The literature review explores optimizing production waste in tobacco manufacturing, emphasizing the integration of lean management and reliability analysis to enhance efficiency and sustainability. lean manufacturing focuses on eliminating non-value-added activities (waste), while reliability analysis improves system performance and equipment effectiveness (Aucasime-Gonzales et al., 2020; Geisbush & Ariaratnam, 2023). despite extensive research in general manufacturing sectors, studies on their application in tobacco production remain scarce (Dewadi et al., 2024). existing literature primarily investigates lean practices in industries like automotive (Aksar et al., 2022), steel processing (Indrawati et al., 2019), and packaging (Dinesh et al., 2022), leaving tobacco-specific waste types, such as tobacco dust, leaf spoilage, and packaging waste, largely unaddressed. a significant gap is the lack of integration between lean and reliability principles. while some studies explore reliability-centered maintenance (RCM) to enhance equipment uptime (Khasanah et al., 2021) or failure mode and effect analysis (FMEA) for risk mitigation (Huang et al., 2020), few examine how these methodologies can complement lean strategies to optimize waste reduction in tobacco manufacturing. research on predictive maintenance (Han et al., 2021) and optimization models (Harbaoui & Khalfallah, 2022) highlights the need for data-driven, proactive reliability approaches, yet many studies rely on traditional tools like value stream mapping (VSM) or Six Sigma without incorporating advanced simulation modeling or Industry 4.0 technologies (Er-Ratby et al., 2024). additionally, the impact of regulatory constraints on waste management practices remains underexplored. while environmental regulations shape production efficiency and waste reduction strategies (Ali et al., 2019), research often neglects lean-driven compliance approaches. studies on secondary raw material utilization (Don et al., 2016) suggest potential sustainability measures but fail to integrate lean methodologies for waste optimization in tobacco manufacturing. similarly, while reliability analysis supports compliance with equipment performance and predictive maintenance regulations, lean frameworks can streamline processes to meet sustainability standards (Sasikumar et al., 2023).this review seeks to bridge these gaps by developing a structured framework that integrates lean methodologies like Just-In-Time (JIT) production, Kaizen, and VSM with reliability approaches including RCM, FMEA, and predictive maintenance (Latinovic

et al., 2020).the study proposes empirical validation of waste optimization techniques in tobacco manufacturing, ensuring effective resource utilization, reduced defects, and increased operational efficiency. future research should focus on Industry 4.0-enabled waste tracking and IoT-driven predictive maintenance, creating a holistic model that adapts lean and reliability principles to the tobacco industry's unique challenges (Bona et al., 2021).

Table 2.1 Summary of the main articles

Author(s)	Title	Method Used	Benefit Derived	Identified Gaps
Dewadi et al, (2024)	Application of Lean Principles in Tobacco Manufacturing	Case study analysis	Highlights how lean methodologies can be adapted to tobacco production	Lacks discussion on integration with reliability strategies
Khasanah et al, (2021)	Reliability-Centered Maintenance (RCM) in Process Industries	Empirical case study	Demonstrates how RCM enhances equipment effectiveness and plant availability	Does not explore integration with lean for waste optimization
Ali et al, (2019)	Impact of Environmental Regulations on Waste Management	Literature review & regulatory analysis	Emphasizes the role of regulations in shaping waste management practices	Lacks direct application of lean methodologies in compliance strategies
Awogbemi et al, (2022)	Challenges in Sustainable Manufacturing	Comparative industry analysis	Identifies key waste management challenges across various industries	Does not focus on tobacco-specific waste concerns
Aksar et al, (2022)	Integration of Value Stream Mapping (VSM) and Simulation for Process Optimization	Case study in automotive sector	Shows how VSM and simulation can improve efficiency and waste reduction	Needs adaptation for tobacco industry applications
Huang et al, (2020)	Improvements in Failure Mode and Effect Analysis (FMEA)	Literature review	Evaluates enhancements in FMEA for identifying failure risks	Lacks industry-specific adaptation, including tobacco manufacturing
Geisbush & Ariaratnam (2023)	Reliability-Centered Maintenance (RCM) Implementation	Systematic review	Provides a structured approach for improving maintenance practices	Does not integrate lean for holistic waste reduction
Indrawati et al, (2019)	Lean Manufacturing Implementation in Steel Processing	Case study	Demonstrates effectiveness of lean in manufacturing efficiency	Needs further exploration for tobacco waste optimization
Er-Ratby et al, (2024)	Predictive Maintenance Optimization	Simulation-based analysis	Shows predictive maintenance's role in improving industrial efficiency	Limited integration of lean strategies for waste reduction

2.19 Gaps from Existing Literature

Research about lean manufacturing and reliability analysis is growing, but studies that combine these two to optimize production waste in tobacco manufacturing are very few. Many papers focus only on lean to reduce process inefficiency ([Aucasime-Gonzales et al., 2020](#)) or just on reliability to improve equipment uptime ([Geisbush & Ariaratnam, 2023](#)). When study separate these two, they miss how machine performance and process efficiency depend on each other in real production. Also, there is not much study about tobacco-specific waste. Most research is on automotive ([Aksar et al., 2022](#)) or steel ([Indrawati et al., 2019](#)), which is very different process. Special waste in tobacco, like tobacco dust, leaf spoilage, and packaging material waste, not well covered. This make it hard to use those study result directly for tobacco industry.

Methodology in many research is also narrow. They mostly use tools like value stream mapping and FMEA only, no integration model or predictive maintenance ([Er-Ratby et al., 2024](#)). This cannot fully capture how machine reliability and waste generation interact. Better approach need more data-driven and also predictive tools.

Theoretical side also weak. Most use linear models and not think about feedback loop or cross-department effect. Systems thinking from engineering could help, but is not common. Also, Industry 4.0 technology like IoT sensors, real-time waste tracking is not used much in this field ([Bona et al., 2021](#)). In many region with low tech infrastructure, research not discuss how to apply these solution in real world.

Overall, there is big need for study that integrate lean and reliability together for tobacco production. Lean aim to remove waste ([Aucasime-Gonzales et al., 2020](#)) and reliability focus on equipment health ([Geisbush & Ariaratnam, 2023](#)), but few study see how they can work together. Most results are from other industry and cannot solve unique problem of tobacco production, like regulation requirement and sensitive raw material. Most study are short-term case studies and no look at long-term effect.

In in summary , existing literature show need for one framework that join lean and reliability to reduce waste in tobacco production. This framework must also use modern technology like predictive maintenance and IoT monitoring ([Han et al., 2021](#)) and be designed for industry-specific waste.

Chapter Three

Research Methodology

3.1 Introduction

Research methodologies provide a structured pathway for investigating complex problems across various industries, enabling researchers to derive actionable insights through systematic approaches. In the context of manufacturing, methodologies often integrate diverse data types to address operational challenges effectively. This study adopts a concurrent mixed-methods design, combining quantitative and qualitative data to explore and mitigate issues in production processes. Specifically, at the National Tobacco Enterprise (NTE), the focus is on enhancing waste reduction and improving machine reliability within the production environment. This comprehensive approach is essential for tackling the intricate inefficiencies present in tobacco manufacturing, aiming to evaluate proposed interventions thoroughly. The expected outcomes include a measurable decrease in production waste, enhanced machine reliability, and improved efficiency across NTE's production lines, contributing to operational excellence and sustainability.

3.2 Study Area

The research focuses specifically on the Make-Pack department of NTE, which is identified as the highest contributor to production waste due to cigarette rejects and non-conformance to manufacturing (NTM) inefficiencies. Addressing waste in this department is crucial, as it has a direct impact on cost reduction and process improvement. The context of the tobacco industry presents unique challenges related to waste management and machine reliability. Insights gained from this research will not only benefit NTE but may also be applicable to similar industries grappling with operational inefficiencies.

3.3 Research Design

Research designs in industrial studies often combine multiple methodologies to provide a holistic understanding of operational phenomena, particularly in sectors where both numerical and experiential data are critical. A mixed-methods design is widely recognized for its ability to integrate quantitative and qualitative approaches, offering a robust framework for analysis (Battista & Torre, 2023; Jilcha Sileyew, 2020). This

study employs such a design to investigate production inefficiencies at NTE, utilizing descriptive observational studies to identify patterns and explanatory experimental studies to uncover root causes of waste and downtime. this approach is particularly suitable for tobacco manufacturing, where production metrics must be complemented. The research framework systematically addresses NTE's operational challenges, starting with a literature review and industry consultations to identify key issues, followed by the formulation of specific objectives tailored to the production context, as illustrated in Figure 3.1 (adapted from [Jilcha Sileyew, 2020](#)). develop a comprehensive understanding of the production environment at NTE, ultimately enabling informed decision-making that can lead to operational improvements and followed by the formulation of specific research objectives.

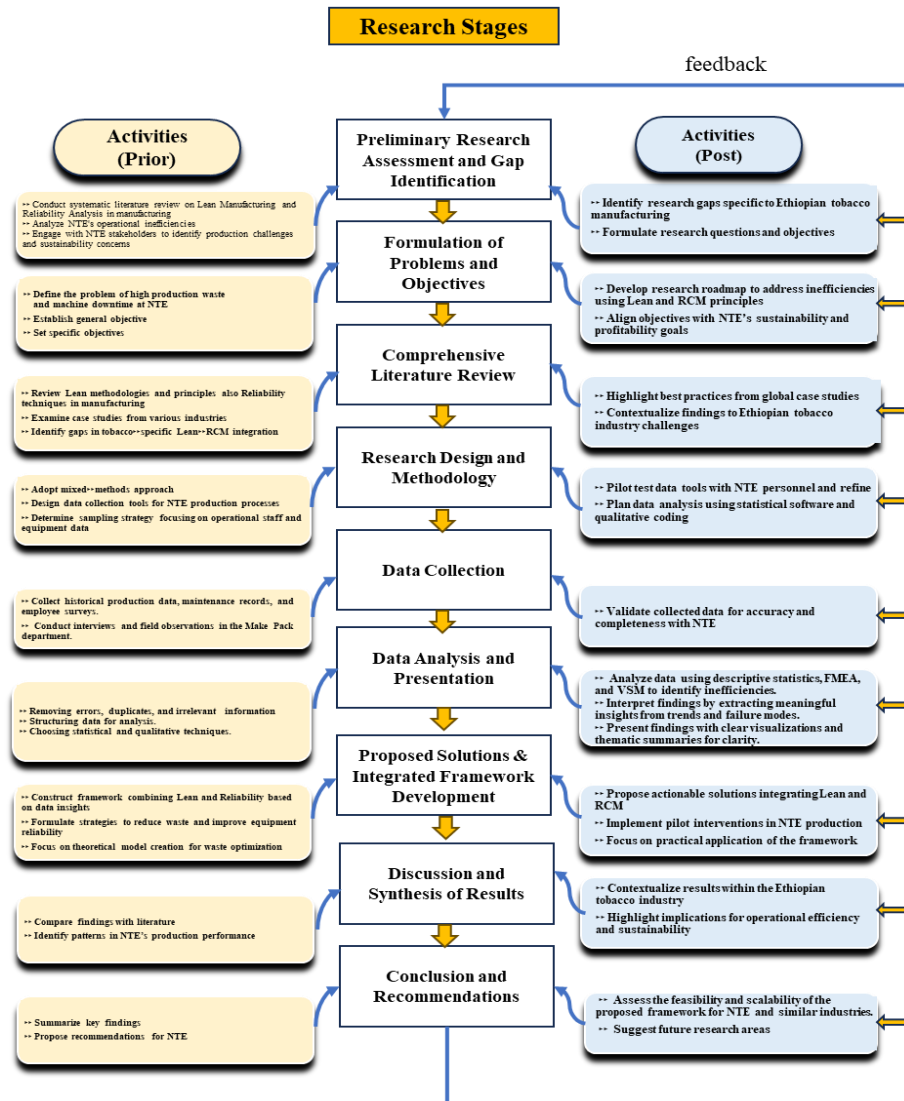


Figure 3.1 Research Design Framework (adapted from (Jilcha Sileyew, 2020)

feedback

3.4 Data Sources

Manufacturing research relies on a wide range of data sources to construct a comprehensive evidence base, ensuring that theoretical insights are effectively combined with practical operational data. This study leverages both primary and secondary data sources to conduct a thorough and reliable analysis of waste reduction and machine reliability at National Tobacco Enterprise (NTE). The integration of these data sources enhances the validity of the research, enabling detailed assessments of existing inefficiencies and guiding future improvements in operational efficiency.

3.4.1 Primary Data Sources

Primary data sources provide real-time insights from NTE's production environment, capturing direct operational experiences from employees and internal systems. These sources include:

Internal Company Records: This data consists of detailed production metrics such as planned versus actual yields, material waste percentages, and machine uptime/downtime logs. Additionally, maintenance logs are reviewed, focusing on equipment failure frequencies, preventive maintenance schedules, and compliance levels to track reliability.

Employee Feedback: Information is collected through surveys, interviews, and focus groups conducted with key personnel, including management staff, shift supervisors, mechanics, electricians, and machine operators. These discussions provide firsthand perspectives on operational inefficiencies, waste reduction strategies, and machine reliability concerns.

Field Observations: Real-time observations within NTE's production facilities enable direct monitoring of workflow dynamics, machine performance, and waste generation. This data is supplemented by photographs and detailed field notes to ensure objective documentation of inefficiencies.

3.4.2 Secondary Data Sources

Secondary data sources provide comparative and contextual insights that complement primary data, offering broader industry perspectives and benchmarks for evaluating NTE's performance. These sources include:

Academic Literature: Published studies on Lean Management and Reliability analysis in engineering and industrial Operations provide a strong theoretical foundation for

the research. these studies highlight best practices, identify gaps in current knowledge, and validate analytical methods used in this investigation.

Industry Benchmarks and Reports: Comparative data from similar manufacturing industries is reviewed to assess how NTE's performance aligns with established standards. this benchmarking helps identify areas for improvement and ensures that recommended interventions align with global best practices.

3.5 Data Collection Methods

Data collection in manufacturing research employs a range of tailored techniques to align with study objectives and operational realities, ensuring accuracy, reliability, and comprehensiveness in results. this study integrates both primary and secondary data collection methods, leveraging quantitative and qualitative approaches to assess waste reduction strategies and machine reliability at NTE.

3.5.1 Primary Data Collection

Primary data collection captures direct operational insights, enabling researchers to analyze real-world inefficiencies with precision.

Questionnaires: Structured questionnaires with **Likert-scale** items are designed to measure employee perceptions of waste reduction strategies, satisfaction with machine reliability, and suggestions for enhancing production efficiency. these questionnaires was distributed through electronic and manual channels to ensure broad participation.

Interviews: Semi-structured interviews are conducted with production managers, technicians, and operators. these interviews include targeted questions designed to extract detailed insights into operational challenges.

Focus Groups: Discussions involving provide a collaborative forum for diverse perspectives on production inefficiencies, fostering in-depth dialogue on waste reduction and equipment reliability.

Field Observations: Direct observations within NTE's production facilities are carried out over two weeks, documenting real-time workflow dynamics, equipment interactions, and sources of waste. this data is further reinforced through photographic documentation and detailed field notes, ensuring objective reporting of findings.

3.5.2 Secondary Data Collection

Secondary data collection offers contextual and comparative insights, complementing primary data to establish a well-rounded analysis.

Literature Review: A structured review of academic articles, industry reports, and internal assessments related to Lean Management and Reliability Analysis is conducted. The literature review process follows a **systematic approach** to ensure rigor and transparency:

- ✚ **Defining the research scope** to focus on Lean Manufacturing and Reliability Analysis.
- ✚ **Collecting relevant literature** from academic databases and industrial case studies.
- ✚ **Organizing and managing sources** using tools like **Zotero** for reference tracking.
- ✚ **Screening and selecting sources** based on relevance to study objectives.
- ✚ **Critically evaluating and extracting key findings** using structured tools like **Excel** for data synthesis.
- ✚ **Synthesizing existing knowledge** to identify overarching themes related to waste reduction and machine reliability.
- ✚ **Identifying research gaps** in tobacco manufacturing and integrating best practices.
- ✚ **Developing a theoretical framework** to support the study's hypotheses.
- ✚ **Structuring and writing the literature review** to ensure coherence and alignment with study goals.

Company Records and Reports: Historical production data is reviewed, focusing on key metrics like planned versus actual yields, material waste percentages, and machine uptime/downtime figures. Additionally, **maintenance logs** detailing equipment failure frequencies, preventive maintenance schedules, and compliance levels are examined to assess existing reliability measures and areas for improvement.

Data Tracking

Data tracking in manufacturing research is fundamental for capturing operational trends, evaluating the effectiveness of interventions, and driving continuous improvement across production systems. This process entails systematic and ongoing monitoring of key performance indicators (KPIs) and operational metrics, providing a dynamic perspective on efficiency, waste management, and equipment reliability. For this study, a robust and meticulously curated data tracking system is implemented to monitor the production processes at the National Tobacco Enterprise (NTE). This system

ensures accurate, timely, and comprehensive data collection that informs strategic initiatives aimed at reducing waste and enhancing machine reliability. The tracking strategy leverages NTE's existing enterprise resource planning (ERP) systems, augmented by manual data recording during field observations, to deliver a longitudinal perspective on performance metrics. This dual approach facilitates a holistic assessment of NTE's operational dynamics, addressing specific challenges.

Key Performance Indicators (KPIs)

The selected KPIs reflect critical aspects of NTE's production performance, enabling a quantitative evaluation of waste reduction and machine reliability efforts:

- ✚ **Production yields:** Compare planned production outputs against actual yields to assess efficiency and identify discrepancies contributing to waste.
- ✚ **Material Waste Percentages:** Measure the proportion of raw materials lost during production to pinpoint sources of inefficiency and guide resource optimization strategies.
- ✚ **Machine Uptime/Downtime Ratios:** Track the operational availability of machinery versus periods of inactivity to evaluate reliability and identify maintenance needs.
- ✚ **Reject Rates Across Production Lines:** Monitor the percentage of defective products across all lines, focusing on the Make-Pack department to assess Machine Reliability and Autonomous Maintenance effectiveness.
- ✚ **Maintenance Intervention Frequencies and Outcomes:** Record the frequency of maintenance activities and their success in restoring equipment performance, providing insights into preventive maintenance efficacy.

Tracking Methods

The tracking methods combine automated systems and manual techniques to ensure comprehensive data capture across NTE's production cycle:

- ✚ **Utilization of NTE's ERP Systems:** Leverage NTE's ERP infrastructure to collect real-time production data, including output rates, machine status, and maintenance schedules, ensuring high accuracy and consistency in automated data streams.
- ✚ **Implementation of Manual Data Recording:** Conduct detailed manual recordings during on-site observations to capture qualitative insights and

operational nuances not accessible through automated systems, such as employee workflows and unanticipated waste sources.

- ✚ **Tracking Material Movement in the Warehouse:** Monitor incoming, outgoing, and returned material quantities to evaluate inventory management efficiency and optimize stock levels across production stages.
- ✚ **Monitoring Initial Production Processes:** Collect data on machine hours, downtime incidents, defective products, and production capacity targets to evaluate Overall Equipment Effectiveness (OEE) and quality management practices, providing a foundation for process optimization.
- ✚ **Monitoring Work-in-Progress (WIP), Packaging, and Intermediate Inventory Stores:** Evaluate inventory quality and management by tracking WIP stages, packaging processes, and intermediate stock levels to identify bottlenecks and waste points.
- ✚ **Tracking Shipping Crates and Finished Goods for Export:** Assess end-of-line production efficiency by monitoring the output of shipping crates and exported finished goods, ensuring alignment with demand and quality expectations.

The implementation of this data tracking system is designed to provide a continuous feedback loop, enabling NTE to adapt and refine its waste reduction and reliability enhancement strategies in real time. The study ensures a balanced approach that captures both quantitative performance metrics and qualitative operational insights, fostering a data-driven culture of improvement within NTE's production environment.

3.6 Sampling Techniques

Sampling helps collect data that represent the target group and match the study goal, which is very important in industry where expert knowledge affects results quality. It allows to study smaller groups but still get meaningful conclusions and save time and resources. In this research, sampling focuses on workers at National Tobacco Enterprise (NTE) to study waste and machine reliability problems. Stratified and purposive sampling are used to cover key roles and also get deep insight from people with technical skill.

3.6.1 Target Population

The sampling framework focuses on employees actively engaged in NTE's production processes, whose roles and expertise are pivotal to understanding and addressing waste

reduction and machine reliability.this population includes:

- ✚ **Operator:** Responsible for operating, monitoring, and performing basic maintenance on production equipment.
- ✚ **Mechanics:** Responsible for equipment maintenance and repair, providing insights into machine reliability issues.
- ✚ **Electricians:** Tasked with electrical system upkeep, contributing expertise on equipment downtime causes.
- ✚ **Shift Leaders:** Oversee daily production activities, offering perspectives on workflow efficiency and waste sources.
- ✚ **Maintenance Supervisors:** Manage maintenance schedules and interventions, key to assessing reliability strategies.

These roles are selected due to their direct involvement in technical and operational - related activities, ensuring the data reflects the operational realities of NTE's production environment. A target Population of 40 employees is targeted, a size deemed sufficient to achieve statistical representativeness while remaining feasible within NTE's operational context, considering the availability and willingness of participants.

3.6.2 Inclusion and Exclusion Criteria

Inclusion Criteria

Participants included in this research hold significant technical and operational roles at NTE such as mechanics, electricians, shift leaders, and maintenance supervisors.they are required to have at least one year of experience at NTE to ensure familiarity with operational processes and relevant challenges.

Exclusion Criteria

Individuals excluded from this research include non-production staff, such as administrative workers and material handlers, to maintain a focus on those with direct operational experience. Additionally, employees with less than one year of experience at NTE are not considered, ensuring that all participants have a sufficient understanding of current dynamics and avoiding gaps in insights.

3.7 Data Analysis Techniques

Data analysis turns raw data into useful insight using statistics and other tools to solve complex industrial problems. It help find inefficiency, improve resource use, and boost equipment performance for continuous improvement. In this study, a well-planned multi-step analysis is used to check data from National Tobacco Enterprise (NTE) and

give strong evaluation of waste reduction and machine reliability efforts.

3.7.1 Quantitative Data Analysis

This component leverages numerical data to provide a statistical foundation for evaluating NTE's production performance, employing advanced software to ensure precision and clarity.

- ✚ **Descriptive Statistics:** Statistical software SPSS and Excel was used to summarize key trends in production waste, yields, and machine uptime/downtime ratios. This method generates a clear overview of operational performance, highlighting patterns critical for identifying immediate areas of concern.
- ✚ **Inferential Statistics:** Rigorous statistical tests, including t-tests, ANOVA, and regression analysis, explore relationships between variables. This approach assesses the impact of Lean Manufacturing practices on waste reduction and the effectiveness of Reliability-Centered Maintenance (RCM) on machine reliability, identifying statistically significant factors that influence operational efficiency.

3.7.2 Qualitative Data Analysis

This section captures the nuanced perspectives of NTE employees, transforming narrative data into thematic insights that complement quantitative findings.

- ✚ **Thematic Analysis:** employed to code and categorize data from interviews and focus groups, systematically identifying key themes and patterns in operational challenges. This process uncovers barriers to waste reduction and employee perceptions of equipment reliability, enriching the study with contextual depth.
- ✚ **Value Stream Mapping (VSM):** visualized the flow of materials and information across NTE's production processes, pinpointing inefficiencies and facilitating targeted interventions to streamline operations.

3.7.3 Machine Reliability Assessment

This specialized section focuses on evaluating and improving equipment performance, employing advanced models to address NTE's reliability challenges.

- ✚ **Failure Analysis:** Failure Mode and Effects Analysis (FMEA) systematically identify potential failures and their causes, followed by Root Cause Analysis (RCA) to investigate underlying issues. This dual approach enhances machine reliability through proactive maintenance strategies.

3.8 Reliability and Validity

Establishing the reliability and validity of research findings is crucial in industrial studies, particularly in mixed-methods research, where integrating quantitative metrics and qualitative narratives demands rigorous validation to ensure credibility and trustworthiness. This study, aimed at optimizing production waste and enhancing operational efficiency at the National Tobacco Enterprise (NTE), employs a comprehensive suite of strategies to safeguard the integrity of its findings, particularly regarding the Make-Pack department's challenges.

Reliability

Reliability ensures the consistency and reproducibility of measurement tools and data analysis processes, which is essential for dependable conclusions.

- ✚ **Internal Consistency:** The reliability of questionnaire items is evaluated using Cronbach's alpha, with a target minimum value of 0.70 to confirm consistent measurement of constructs like employee perceptions of waste reduction strategies and machine reliability. This statistical approach ensures cohesive responses from NTE employees, including mechanics and shift supervisors.

Validity

Validity verifies that the research accurately measures the intended constructs and aligns with real-world phenomena, which is crucial for the study's applicability at NTE.

- ❖ **Content Validity:** Questionnaires are developed based on a thorough review of existing literature on Lean Manufacturing and Reliability-Centered Maintenance (RCM), validated by subject matter experts, including NTE management and academic researchers. This ensures comprehensive coverage of relevant constructs like waste reduction and equipment performance.
- ❖ **Construct Validity:** Assessed through factor analysis for quantitative data and triangulation for qualitative data, this approach cross-verifies findings from employee feedback, field observations, and interview insights, confirming the consistency and theoretical grounding of the constructs.
- ❖ **Criterion Validity:** Study results are compared against industry benchmarks and prior research on waste reduction and reliability in manufacturing, validating findings within NTE's operational context.

3.9 Ethical Considerations

This study at National Tobacco Enterprise (NTE) follows strict ethical rules to protect

participant rights, dignity, and privacy. Company information is kept confidential and shared only with permission. Employees in Make-Pack department like supervisors, mechanics, electricians, and operators give verbal consent before interviews and answer willingly. Researcher treat participants with respect and keep communication open to build trust and honest sharing.

Informed Consent

Every survey, interview and focus group respondent was made fully aware of the purpose behind the study, namely optimization of the production waste and operational efficacy. Their rights were explained to them on the procedures and the fact that they had the right to withdraw at whatever point they wanted to and it would not count was made known to them, making the participation voluntary.

Confidentiality and Anonymity.

The responses of participants were anonymized together with company data as part of the analysis and reporting to safeguard identities and promote honest feedback. The results of the surveys were coded to strip the identifiable information to ensure that the final report was anonymous.

Transparency in Research

Consent forms and briefings describe the purpose of the study, its methods, and the usage of data that the study used. This openness created a sense of trust among the NTE employees and helped them to volunteer information about operational issues.

Result Interpretations

Interpreting manufacturing research results is essential for deriving actionable insights that address operational challenges and guide strategic improvements at the National Tobacco Enterprise (NTE).this study applies targeted analytical tools: histograms to reveal high-impact operational zones, cause-and-effect (Ishikawa) diagrams to trace technical inefficiencies to their root causes, Pareto charts to prioritise the most significant production issues, and scatter plots to uncover relationships between operational variables. By integrating these quantitative analyses with qualitative insights from employee feedback, the approach delivers a comprehensive understanding of waste reduction and machine reliability.

Chapter Four

Data Analysis and Results

4.1 Introduction

This chapter presents the findings from a case study conducted at the National Tobacco Enterprise (NTE), focusing on production waste and operational efficiency in the Make-Pack department. The results are derived from the mixed-methods approach outlined in Chapter three encompassing three years (2022-2024) of monthly quantitative data totaling 30 months from internal records, qualitative insights from interviews, focus groups, and field observations, Value Stream Mapping (VSM), and reliability analyses, including Failure Mode and Effects Analysis (FMEA), Root Cause Analysis (RCA), and Pareto Analysis. RCA is employed to uncover the underlying causes of key production issues, while Pareto Analysis prioritizes the most significant contributors to waste and downtime, aligning with the methodology's emphasis on identifying critical inefficiencies. The chapter is structured to present the analyzed data, interpret the findings, and discuss their implications in relation to the research objectives. These findings provide a comprehensive understanding of operational challenges and opportunities for improvement at NTE.

4.2 Case Company Profile

National Tobacco Enterprise (NTE), operating under Japan Tobacco International (JTI) Ethiopia, stands as the country's leading tobacco manufacturing company with a rich operational history spanning over eight decades since its establishment in 1942 as the "Tobacco Regie." Following a landmark USD 1 billion acquisition by Japan Tobacco International in 2017 representing the largest private sector investment by a Japanese company in Ethiopian history, NTE operates under a strategic ownership structure with JTI holding 71% and Sheba Company retaining 29% of shares. Headquartered in Addis Ababa with its primary manufacturing facility strategically located on Kilinto Special Economic Zone, the enterprise demonstrates vertical integration through its comprehensive tobacco value chain, managing five large-scale tobacco farms across Robi, Billate, Hawassa, Wolayta, and East Shoa regions while supporting over 8,000 tobacco outgrowers nationwide. With an annual production capacity approaching 20 billion cigarettes and flagship brands including Nyala, Nyala Premium, Elleni, Gissila,

Delight, and the internationally recognized Winston, NTE maintains its position as Ethiopia's sole legal tobacco manufacturer, achieving 98% local production of the 8.5 billion cigarettes sold in 2020. The enterprise serves as a significant economic contributor, providing direct employment to over 670 permanent employees and 3,305 temporary workers, while generating substantial revenue streams that position it among Ethiopia's top-performing industrial enterprises in terms of annual turnover and profitability, thereby reinforcing its critical role in the country's manufacturing sector and broader economic development agenda.

4.3 Case Company Manufacturing Process Flow

The Make-Pack department at National Tobacco Enterprise (NTE) serves as the focal point of this study due to its critical role in cigarette production and its significant contribution to material waste and machine downtime. NTE employs a structured, multi-stage manufacturing process for Ready-Made Cigarettes (RMC), designed to meet Japan Tobacco International (JTI) Quality Standards and ensure compliance with safety, food-grade handling, and environmental protocols. The process begins with the request and staging of Non-Tobacco Materials (NTMs) from the NTM warehouse. These include cigarette filter tips, aluminum foil, tear tape, and packaging films. CFTs are delivered to the production line, where the Manual Filter Feeder loads them into the Filter Making Unit. From there, the Manual Tobacco Feeder supplies tobacco to the Cigarette Maker (e.g., GD121 machines), operated by Maker Operators. This stage forms the cigarette rods, which are subject to inline quality inspection by both the Maker Operator and Quality Analyst. Deviations such as loose ends or missing filters are flagged, and reclaimed CFTs may be reused if within tolerance. Formed cigarettes are transferred to the Cigarette Packer (e.g., X1/X2/X500), where Packer Operators assemble 20-stick packs, incorporating foil and branded labels. Defective packs, those with missing sticks, misaligned filters, or loose ends are rejected and sent to the Cigarette Reject Station. Finished packs are then sealed in poly film by the Cellophane Machine, which applies tear tape and protects against moisture and off-flavors. Next, packs are bundled into sets of ten using necked overwrap poly film, and transferred to the Manual Boxer or Case Packer Machine, where 50 bundles are filled into shipping cases. These cases are sealed, labeled for traceability, and manually palletized by operators in a cross-stacked arrangement of 24 cases per pallet. Finally, the Finished Goods (FG) pallets are transported to the FG warehouse for dispatch.

NTE Multi-stage Cigarette Manufacturing Flow in Make-Pack Department

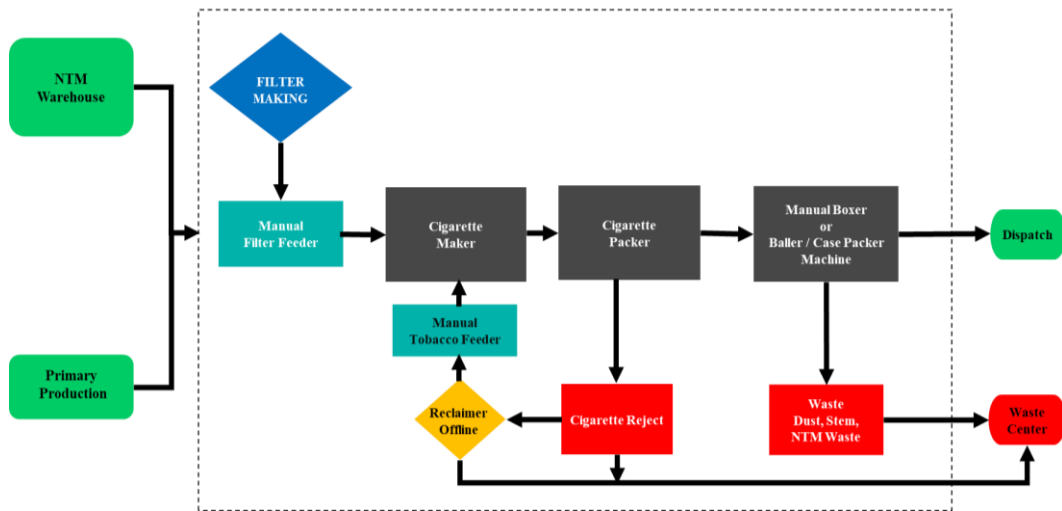


Figure 4.1 NTE Multi-stage Cigarette Manufacturing Flow

Throughout the process, waste such as dust, stem, and NTM scraps is collected and routed to the Waste Center, while reclaimable materials are sent to the Reclaimer Station for potential reuse. The entire flow is governed by Production Control, which coordinates material requests, delivery schedules, and quality checkpoints in alignment with JTI's operational standards.

4.4 Quantitative Findings

This section provides an analysis of quantitative data collected from NTE's internal records over a 30-month period (2022-2024), specifically for the Make-Pack department. Descriptive and inferential statistics are used to highlight trends and deviations in key performance indicators (KPIs). These findings lay the groundwork for identifying improvement opportunities and directly support the research aim of optimizing waste and enhancing efficiency. The data sources include production logs, maintenance records, and outputs from NTE's analytics department, as outlined in Chapter Three. The descriptive statistics for the key performance indicators (KPIs) over the 30-month period (2022-2024) are presented in Table 4.1. This table summarises the overall range, average, and variability for each metric, providing an initial overview of NTE's operational performance compared to its targets.

Table 4.1 Descriptive Statistics of Key Performance Indicators

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Reject_Rate (%)	30	2.84	8.88	5.0193	1.69001
Reject_Rate_Target (%)	30	3.0	3.5	3.200	.2491
OEE (%)	30	25.76	47.36	35.8550	5.93568
OEE_Target (%)	30	43.0	44.5	43.900	.7474
Year	30	2022	2024	2022.80	.761
Production_Yield (%)	30	81.25	94.28	89.3977	4.43320
Production_Yield_Target (%)	30	91.5	97.0	94.000	2.2050
Production_Volume_Units	30	218620000.0	428460000.0	311870333.3	61553965.70
NTM_Waste_Rate (%)	30	1.12	6.67	3.3833	1.50107
NTM_Waste_Rate_Target (%)	30	1	1	1.00	.000
NTM_Yield (%)	30	93.33	98.88	96.7757	1.54631
NTM_Yield_Target (%)	30	99	99	99.00	.000
Valid N (listwise)	30				

The descriptive statistics reveal that, on average, NTE's Reject Rate (%) (M = 5.0193) and NTM Waste Rate (%) (M = 3.3833) are considerably higher than their respective targets of 3.20% and 1.00%, indicating persistent challenges in waste management. conversely, OEE (%) (M = 35.8550) and Production yield (%) (M = 89.3977) consistently fall below their targets of 43.90% and 94.00%, respectively. the standard deviations highlight significant variability in performance, particularly for Reject Rate (SD = 1.69001) and OEE (SD = 5.93568), suggesting instability in operations and an inability to maintain consistent efficiency over time. the NTM yield (M = 96.7757) also averages below its 99% target, reinforcing the issue of material utilisation. these overall averages underscore chronic underperformance across critical KPIs, necessitating in-depth investigation into underlying causes related to process inefficiencies and equipment unreliability.

4.4.1 Production-Waste KPIs

Tracking production waste metrics is crucial for manufacturing industries, particularly in materials-intensive sectors like tobacco production, which are subject to stringent regulations. these metrics are essential for cost reduction, enhancing operational efficiency, and advancing sustainability goals. High levels of waste indicate resource loss, diminished productivity, and reduced capacity utilisation, directly impacting a company's financial health. the pervasive issue of excessive material rejection at NTE is complex, manifesting through high reject rates of cigarettes and significant Non-Tobacco Material (NTM) waste.

4.4.1.1 Cigarette Reject Rates

The findings concerning cigarette reject rates at NTE over the 30-month period (2022-2024) reveal persistent challenges in maintaining quality standards.

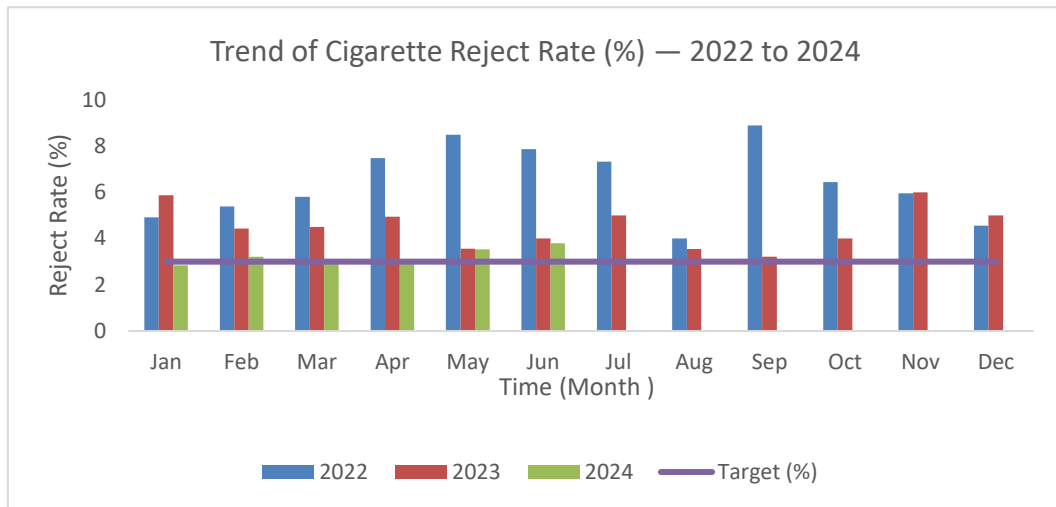


Figure 4.2 Trend of Cigarette Reject Rate (Percentage) (2022-2024) Source: (NTE)

company data consistently shows that NTE's material rejection rate has fluctuated between 4% and 7% in the last two years, which is considerably higher than the company's targets of 3% (for 2023) or 3.5% (for 2022), and well above the global industry standard of 2-3% achieved by companies implementing lean manufacturing practices. In 2022, the reject rate was particularly high, reaching 8.49% in May and peaking at 8.88% in September, significantly exceeding the 3.5% target for the year. the average reject rate for 2022 was approximately 6.22%. While 2023 saw some improvements compared to 2022, NTE continued to struggle with maintaining a low reject rate consistently throughout the year. the rates varied from a low of 3.22% in September to a high of 6% in November, with an average of approximately 4.34%, still above the 3% target for the year. For the available data in 2024 (January to July), reject rates show a general trend closer to the target, with values like 2.84% in January, 3.05% in March, and 3.01% in April. However, it still reached 3.8% in June, and the average for this partial period was approximately 3.17%. the inconsistent performance, often exhibiting seasonal trends with higher reject rates at the start and end of the year, highlights an ongoing issue. this high waste rate negatively impacts profitability by increasing raw material consumption and incurring foreign currency costs, while also raising environmental concerns due to increasing regulations and sustainability expectations. cigarette rejects, which fail to meet quality standards (e.g., missing

cigarettes, loose ends, or missing filters), contribute to substantial waste by discarding valuable tobacco and packaging materials.

To statistically assess the deviation of NTE's reject rate from its target, a paired samples t-test was conducted, comparing the observed monthly reject rates with their corresponding targets over the 30-month period, the paired samples t-test indicates a statistically significant mean difference between NTE's Reject Rate (%) and its Reject Rate Target (%) ($t(29) = 6.518, p < .001$).

Table 4.2 Paired Samples Test for Reject Rate Rate vs. target Target

		Paired Samples Test							
		Paired Differences							
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	Reject_Rate (%) - Reject_Rate_Target (%)	1.81933	1.52891	.27914	1.24843	2.39024	6.518	29	<.001

the average observed reject rate is 1.81933 percentage points higher than the target, with a 95% confidence interval ranging from 1.24843% to 2.39024%. this statistically significant deviation confirms that NTE's material rejection consistently exceeds acceptable levels, contributing to substantial waste and reinforcing the need for targeted interventions to align with both company goals and global industry standards.

4.4.1.2 Non-Tobacco Material Waste Rates

Non-Tobacco Material (NTM) waste constitutes another significant component of production waste at NTE, primarily occurring due to overuse, damage, or process inefficiencies. the NTMs encompass imported materials such as label reels, end labels, parceling straps, pre-cut reel straps, aluminium foil, polypropylene film, polypropylene tear tape, and glue for labels. these packaging materials are frequently discarded because of the aforementioned inefficiencies, further exacerbating the overall waste problem. In 2022, NTM waste rates were high, ranging from a low of 2.61% in December to a peak of 6.67% in September. this corresponded to NTM yields significantly below the 99% target, often in the 93-94% range, with an average NTM yield of approximately 95.04% for the year. In 2023, there was a noticeable reduction in NTM waste compared to 2022, with rates ranging from 1.12% in December to a high of 3.8% in September. the NTM yields in 2023 were generally higher than in 2022, mostly staying above 97%, with an average of approximately 97.43%.

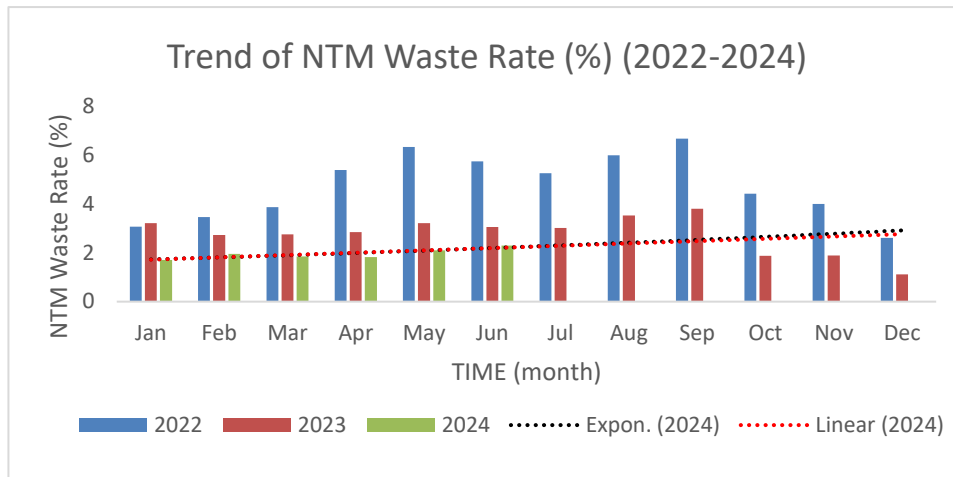


Figure 4.3 Trend of Non-Tobacco Material (NTM) Waste Rate (2022-2024)

Source: (NTE)

For 2024 (January to June), NTM waste rates appear lower, ranging from 1.71% in January to 2.29% in June. corresponding NTM yields are closer to the 99% target, with values like 98.29% in January and 97.71% in June, averaging approximately 98.01% for the period, this consistent presence of NTM waste directly exacerbates the overall waste problem, adding to operational costs and impacting the company's environmental footprint. to ascertain the statistical significance of NTM waste and yield deviations from targets, paired samples t-tests were performed.

Table 4.3 Paired Samples Test for NTM Waste Rate vs. target and NTM yield vs. target

		Paired Samples Test								
		Paired Differences			95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)	
Pair 1	Reject_Rate (%) - Reject_Rate_Target (%)	1.81933	1.52891	.27914	1.24843	2.39024	6.518	29	<.001	
Pair 2	OEE (%) - OEE_Target (%)	-8.04500	5.35092	.97694	-10.04307	-6.04693	-8.235	29	<.001	
Pair 3	Production_Yield (%) - Production_Yield_Target (%)	-4.60233	2.82730	.51619	-5.65807	-3.54660	-8.916	29	<.001	
Pair 4	NTM_Waste_Rate (%) - NTM_Waste_Rate_Target (%)	2.38333	1.50107	.27406	1.82282	2.94384	8.697	29	<.001	
Pair 5	NTM_Yield (%) - NTM_Yield_Target (%)	-2.22433	1.54631	.28232	-2.80173	-1.64693	-7.879	29	<.001	

The paired samples t-test for NTM Waste Rate (%) shows a statistically significant mean difference from its target ($t(29) = 8.697, p < .001$), with the observed rate being 2.38333 percentage points higher than the 1% target.

Similarly, the NTM yield (%) is statistically significantly lower than its 99% target ($t(29) = -7.879, p < .001$), averaging 2.22433 percentage points below the target. These results underscore a consistent challenge in managing non-tobacco materials efficiently, leading to considerable waste that contributes to increased operational costs and a larger environmental footprint.

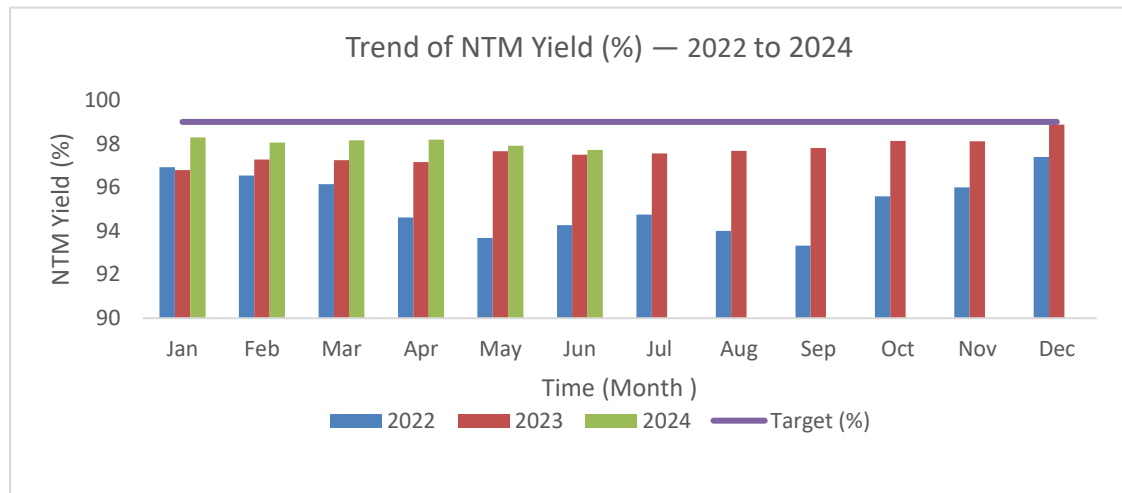


Figure 4.4 Monthly NTM yield Percentages (2022-2024) vs. target Source: (NTE)

4.4.2 Operational Efficiency KPIs

Operational efficiency metrics are crucial for assessing the overall productivity, resource utilisation, and ability of a manufacturing enterprise to maintain competitiveness in a dynamic market. At NTE, frequent machine breakdowns and long downtimes are identified as significant contributors to inefficiency, directly impacting production output and overall performance

4.4.2.1 Overall Equipment Effectiveness (OEE)

The Overall Equipment Effectiveness (OEE) trend at NTE reveals significant operational challenges that have adversely affected performance and profitability. OEE values represent a comprehensive measure integrating availability, performance, and quality into a single metric. NTE's OEE consistently falls below the company's targets of 44.5% (for 2023) and 43% (for 2022). There were wide fluctuations in OEE values, ranging from a low of 25.76% in September 2022 to a high of 47.36% in October 2023. Seasonal trends indicate improvements in the middle of the year, but declines at the start and end of the year. In 2022, the average OEE was approximately **30.69%**, significantly below target. For 2023, the average OEE improved to approximately **39.7%** but remained below target.

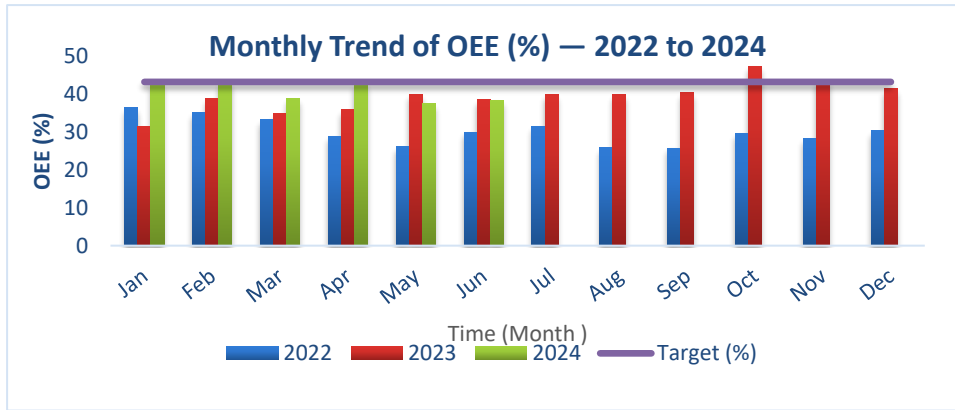


Figure 4.5 Overall Equipment Effectiveness Trend (2022-2024) Source: (NTE)

In 2024 (partial data, January to July), OEE continues to fluctuate, ranging from 37.47% in May to 43.21% in July, with an average of approximately **40.81%**, still predominantly below the 44.5% target for 2024. These persistent inefficiencies strongly suggest underlying issues with machine maintenance, excessive downtime, and inefficient resource utilisation, leading to increased production disruptions and reduced overall output. The problem statement explicitly notes that current maintenance practices and process workflows at NTE are insufficient to solve these problems. A paired samples t-test was conducted to statistically evaluate the deviation of NTE's OEE from its set targets.

Table 4.4 Paired Samples Test for (OEE) from Set Targets

Paired Differences	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference	t	df	Sig. (2-tailed)
OEE (%) - OEE Target (%)	-8.04500	5.35092	.97694	Lower: -10.04307, Upper: -6.04693	-8.235	29	.000

The paired samples t-test reveals a highly statistically significant mean difference between NTE's OEE (%) and its OEE Target (%) ($t(29) = -8.235, p < .001$). The observed OEE is, on average, 8.04500 percentage points below the target, with a 95% confidence interval ranging from -10.04307% to -6.04693%. This substantial and consistent underperformance confirms that NTE's operational efficiency is significantly below desired levels, highlighting chronic issues related to availability, performance, and quality, which justify the need for robust improvement strategies.

4.4.2.2 Interrelationships between Key Performance Indicators (KPIs)

To understand how Overall Equipment Effectiveness (OEE) influences production waste, correlation and linear regression analyses were conducted. OEE is considered a primary independent variable due to its comprehensive nature in reflecting equipment performance, which is hypothesized to impact reject rates and NTM waste directly.

Table 4.5 Correlations between Key Performance Indicators

		Correlations				
		Reject_Rate (%)	OEE (%)	Production_Yield (%)	NTM_Waste_Rate (%)	NTM_Yield (%)
Reject_Rate (%)	Pearson Correlation	1	-.713**	-.734**	.747**	-.811**
	Sig. (2-tailed)		<.001	<.001	<.001	<.001
	N	30	30	30	30	30
OEE (%)	Pearson Correlation	-.713**	1	.815**	-.836**	.884**
	Sig. (2-tailed)	<.001		<.001	<.001	<.001
	N	30	30	30	30	30
Production_Yield (%)	Pearson Correlation	-.734**	.815**	1	-.835**	.897**
	Sig. (2-tailed)	<.001	<.001		<.001	<.001
	N	30	30	30	30	30
NTM_Waste_Rate (%)	Pearson Correlation	.747**	-.836**	-.835**	1	-.966**
	Sig. (2-tailed)	<.001	<.001	<.001		<.001
	N	30	30	30	30	30
NTM_Yield (%)	Pearson Correlation	-.811**	.884**	.897**	-.966**	1
	Sig. (2-tailed)	<.001	<.001	<.001	<.001	
	N	30	30	30	30	30

** Correlation is significant at the 0.01 level (2-tailed).

The correlation analysis reveals strong and statistically significant relationships between OEE and the waste-related KPIs. A strong negative correlation exists between OEE and Reject Rate (%) ($r = -.713$, $p < .001$), indicating that as OEE increases, the cigarette reject rate tends to decrease. Similarly, there is a very strong negative correlation between OEE and NTM Waste Rate (%) ($r = -.836$, $p < .001$), suggesting that higher OEE is associated with significantly lower NTM waste. conversely, a very strong positive correlation is observed between OEE and NTM yield (%) ($r = .884$, $p < .001$), demonstrating that improvements in OEE are highly correlated with increased NTM yield. these significant correlations support OEE's role as a crucial independent variable influencing both types of production waste.

4.4.2.3 Linear Regression Analysis: Predicting Reject Rate (%) from OEE (%)

A linear regression analysis was conducted to examine whether Overall Equipment Effectiveness (OEE %) significantly predicts cigarette reject rate (%). Reject rate was treated as the dependent variable, and OEE % as the independent variable.

Table 4.6 Regression Analysis Summary for Reject Rate

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.713 ^a	.508	.490	1.20667

a. Predictors: (Constant), OEE (%)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	42.058	1	42.058	28.885	<.001 ^b
	Residual	40.769	28	1.456		
	Total	82.828	29			

a. Dependent Variable: Reject_Rate (%)

b. Predictors: (Constant), OEE (%)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12.294	1.371		8.965	<.001
	OEE (%)	-.203	.038	-.713	-5.375	<.001

a. Dependent Variable: Reject_Rate (%)

The regression results indicate that OEE accounts for approximately half of the observed variability in cigarette reject rates ($R^2 = 0.508$, or 50.8%). The model is statistically significant ($F(1, 28) = 28.885$, $p < 0.001$), and the unstandardized coefficient for OEE is 0.203 ($p < 0.001$). This implies that each one-percentage-point improvement in OEE corresponds to an expected reduction of approximately 0.20 percentage points in reject rate. In practical terms, improvements in equipment availability, performance, and quality drive substantial reductions in material rejection, directly supporting Lean objectives of defect elimination and cost minimization.

A second linear regression analysis explored whether OEE % predicts Non-Tobacco Material (NTM) yield (%), using NTM yield as the dependent variable.

Table 4.7 Regression Analysis Summary for Reject Rate

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.884 ^a	.781	.773	.73595

a. Predictors: (Constant), OEE (%)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	54.176	1	54.176	100.025	<.001 ^b
	Residual	15.165	28	.542		
	Total	69.341	29			

a. Dependent Variable: NTM_Yield (%)

b. Predictors: (Constant), OEE (%)

This second model demonstrates even stronger explanatory power: OEE accounts for 78.1% of the variability in NTM yield ($R^2 = 0.781$).the regression is highly significant ($F(1, 28) = 100.025, p < 0.001$), with an unstandardized coefficient of +0.230 ($p < 0.001$).this indicates that for every one-percentage-point improvement in OEE, NTM yield increases by roughly 0.23 percentage points.the result reinforces that equipment reliability and stable machine performance directly translate into better material utilization and reduced waste, which are central goals of both Lean and Reliability frameworks.these regression findings provide empirical evidence that chronic equipment unreliability is a key driver of both high cigarette reject rates and low NTM yield. Rather than isolated process issues, the data reveal an interdependent system where low OEE not only disrupts throughput but also undermines material efficiency.the results highlight the urgent need to strengthen reliability-centered maintenance strategies to improve OEE and, by extension, achieve measurable gains in quality and resource utilization.

4.4.2.4 Production Yield and Production Volume

The company's production yield trend data further highlights NTE's struggle to maintain consistent production efficiency. Actual yields often fall short of the 95% target (for 2023) and 91.5% target (for 2022). For 2022, monthly production yields ranged from 81.25% (May) to 91.34% (November), with an annual average of approximately 86.46%, falling short of the 91.5% target. In 2023, yields improved but still did not consistently meet the 95% target, ranging from 89.58% (April) to 94.82% (November and December).the average yield for 2023 was approximately 92.4%. partial data for 2024 (January to July) shows yields generally closer to the target, ranging from 92.39% (May) to reaching 97% in July, which is notably above the 95% target.the average for this period was approximately 93.69%. clear seasonal changes in production yield, with higher yields typically seen in the middle of the year and lower yields at the start and end, indicate instability in operations and inefficiencies in maintaining a steady output, A paired samples t-test was performed to determine if NTE's production yield significantly deviates from its targets

Table 4.8 Paired Samples Test for Production Yield vs. target

		Paired Samples Test							
				Paired Differences					
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	Reject_Rate (%) - Reject_Rate_Target (%)	1.81933	1.52891	.27914	1.24843	2.39024	6.518	29	<.001
Pair 2	OEE (%) - OEE_Target (%)	-8.04500	5.35092	.97694	-10.04307	-6.04693	-8.235	29	<.001
Pair 3	Production_Yield (%) - Production_Yield_Target (%)	-4.60233	2.82730	.51619	-5.65807	-3.54660	-8.916	29	<.001
Pair 4	NTM_Waste_Rate (%) - NTM_Waste_Rate_Target (%)	2.38333	1.50107	.27406	1.82282	2.94384	8.697	29	<.001
Pair 5	NTM_Yield (%) - NTM_Yield_Target (%)	-2.22433	1.54631	.28232	-2.80173	-1.64693	-7.879	29	<.001

The paired samples t-test demonstrates a highly statistically significant mean difference between NTE's Production Yield (%) and its Production Yield Target (%) ($t(29) = -8.916$, $p < .001$).the observed production yield is, on average, 4.60233 percentage points below the target, with a 95% confidence interval ranging from -5.65807% to -3.54660%.this consistent shortfall in production yield signifies chronic operational inefficiencies and an inability to consistently achieve planned output, directly impacting profitability and resource utilisation

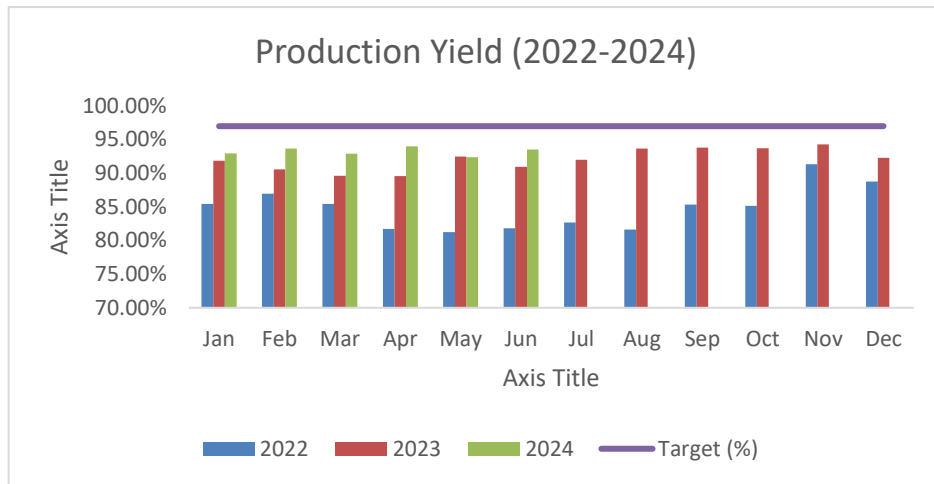


Figure 4.6 Production Yield Trend (2022-2024)

Source: (NTE)

Regarding Production Volume, internal reports show "many time machine failures" which cause unplanned stoppages, significantly impacting production output and efficiency. These breakdowns lead to capacity loss, reducing OEE. These frequent breakdowns and prolonged downtimes are a major factor contributing to NTE's operational inefficiencies, leading to increased production disruptions and a reduction in overall output.

Table 4.9 Monthly Production Volume (2022-2024)

Year	2024	2023	2022
Jan	248,670,000	283,230,000	249,100,000
Feb	378,400,000	290,030,000	253,700,000
Mar	259,950,000	425,760,000	249,000,000
Apr	426,020,000	390,840,000	238,160,000
May	280,910,000	365,330,000	281,910,000
Jun	311,510,000	371,410,000	265,120,000
Jul		266,230,000	338,140,000
Aug		386,080,000	249,830,000
Sep		300,180,000	218,620,000
Oct		428,460,000	293,400,000
Nov		321,260,000	304,310,000
Dec		366,900,000	313,650,000
Annual Planned Volume in billion (stick)	3.9	3.8	3.6

Source: (NTE)

The production volume data illustrates the actual output in relation to planned volumes. While there are fluctuations, the consistent shortfalls in OEE and production yield directly translate into missed production targets and reduced overall output volume. This implies that the identified inefficiencies in equipment performance and process stability directly constrain NTE's ability to meet its planned production capacity, impacting market supply and revenue generation. Addressing the root causes of low OEE and inconsistent yields, as indicated by the prior analyses, is crucial for optimising production volume and improving overall throughput.

The quantitative findings collectively underscore a chronic state of underperformance across the Make-Pack department at NTE, manifesting in consistently high production waste and low operational efficiency. The statistically significant deviations of cigarette reject rates and NTM waste rates from their targets confirm that NTE is grappling with substantial material losses that directly impact profitability and environmental sustainability. Simultaneously, the persistent shortfall in Overall Equipment Effectiveness (OEE) and Production Yield highlights fundamental issues with equipment uptime, performance, and process stability as explicitly stated in the problem context

4.5 Equipment Reliability Assessment

This section delves into the causes of equipment failures and their impact on waste and operational efficiency at the National Tobacco Enterprise (NTE). It directly addresses Research Question 2: "What are the primary causes of production reject at the National Tobacco Enterprise?" by examining how machine malfunctions contribute to defective products, material waste, and production halts. Furthermore, this analysis supports Specific Objective 4: "To evaluate the role of Reliability-Centered Maintenance (RCM) in optimizing equipment performance and minimizing production disruptions." Through RCM principles, the findings highlight opportunities for proactive interventions to enhance machine uptime and reduce non-tobacco material (NTM) waste. This assessment integrates Failure Mode and Effects Analysis (FMEA), Root Cause Analysis (RCA), and Weighted Pareto Analysis, as detailed in the methodology chapter. FMEA identifies potential failure modes and their effects, RCA uncovers underlying causes, and Weighted Pareto Analysis prioritizes issues by weighting frequency against downtime impact, enabling targeted improvements.

4.5.1 Failure Mode Pareto (FMEA Output)

FMEA serves as a systematic, proactive tool for identifying potential failure modes in manufacturing systems, evaluating their causes and effects on operational performance, safety, and product quality. In this context, it assesses how failures in cigarette production equipment Pareto Analysis complements FMEA by prioritizing these modes based on a weighted impact formula:

$$\text{Weighted Impact} = \text{Frequency (occurrences)} * \text{Downtime (hours)}$$

To determine how much each failure mode contributes to the overall performance loss, Cumulative Percentage is calculated as:

$$\text{Cumulative Percentage (\%)} = \frac{\sum_{j=1}^i (x_j \cdot w_j)}{\sum (x_i \cdot w_i)} \times 100$$

Where: x_j = Frequency of failure mode j

w_j = Downtime (hours) of failure mode j

$\sum_{j=1}^i (x_j \cdot w_j)$ = Cumulative weighted impact up to failure mode i

$\sum (x_i \cdot w_i)$ = Total weighted impact across all failure modes

This ensures that stoppages are sorted by their weighted contribution, following the 80/20 rule (Pareto principle), allowing the identification of the "vital few" 'problems responsible for most losses. additionally, each failure mode is assigned a Risk Priority Number (RPN):

$$RPN = \text{Severity (Sev)} \times \text{Occurrence (Occ)} \times \text{Detection (Det)}$$

- ✚ Severity (Sev): normalized average downtime per event (higher = more critical impact)
- ✚ Occurrence (Occ): normalized frequency (higher = more frequent)
- ✚ Detection (Det): fixed at 5 (moderate detectability across NTE equipment)

The data for this analysis is derived from NTE's comprehensive maintenance logs and equipment failure reports spanning 30 months, encompassing over 228,000 failure incidents across Makers, Packers, and Cellophaners. these records capture real-time downtime, frequency, and associated rejects, allowing for a robust evaluation aligned with industry standards in tobacco manufacturing, where common issues include residue buildup, mechanical wear, and related defects.

4.5.1.1 Failure Modes (Weighted Pareto + FMEA) for Packer

Packer machines assemble and wrap finished cigarettes into packets using foils, labels, and other non-tobacco materials (NTM). As high-speed packaging systems, stoppages here directly produce defective packs, elevate NTM waste, and disrupt downstream flow. Reliability is critical to minimizing scrap and sustaining throughput.

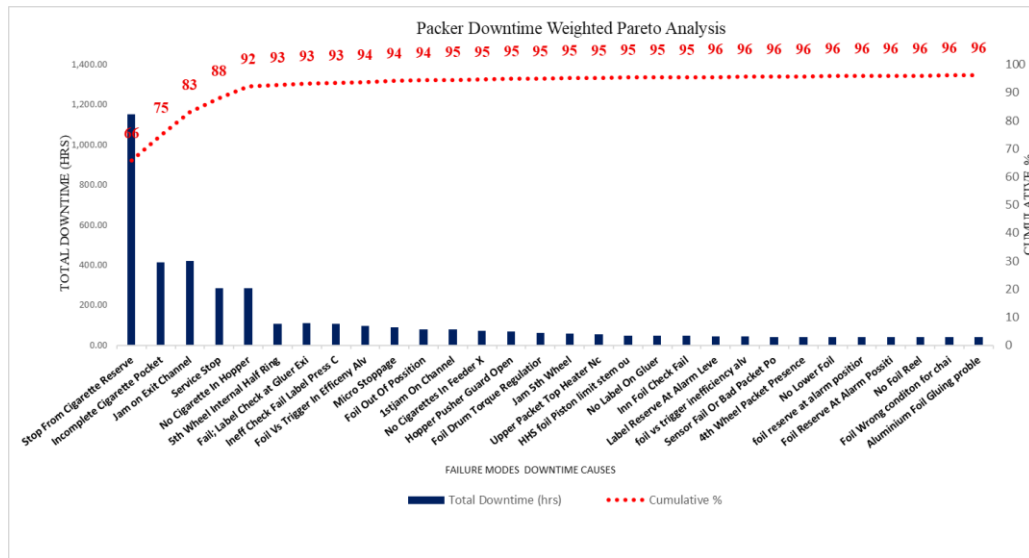


Figure 4.7 Weighted Pareto Analysis of Packer Machine Downtime Causes

The FMEA combined with Weighted Pareto Analysis shows that a few failure modes dominate performance losses. "Stop From Cigarette Reserve" (RPN 146) is the most critical, followed by "Jam on Exit Channel" (RPN 68) and "Incomplete Cigarette Pocket" (RPN 51). Together, these account for over one-third of cumulative downtime, driving significant losses in OEE and packaging efficiency.

Table 4.10 Failure Modes (Weighted Pareto + FMEA) for Packer Machines

Failure Mode	Freq (w _i)	Total Downtime hrs (x _i · w _i)	Weighted Downtime	Cumulative %	WAD hrs	Sev	Occ	Det	RPN	Priority
Stop From Cigarette Reserve	34981	1152.9	1152.9	21.07	0.033	2.92	10.00	5	146	1
Jam on Exit Channel	11977	419.5	419.5	28.74	0.035	3.48	3.93	5	68	2
Incomplete Cigarette Pocket	13305	413.1	413.1	36.29	0.031	2.40	4.28	5	51	5
No Cigarette In Hopper	9149	285.3	285.3	41.51	0.031	2.44	3.18	5	39	12
Service Stop	10976	283.9	283.9	46.69	0.026	1.00	3.67	5	18	63
Label Jam At Gluer Exit	3232	110.9	110.9	48.72	0.034	3.28	1.62	5	27	27
Fail, Label Check at Gluer Exist	2364	108.5	108.5	50.70	0.046	6.42	1.39	5	45	9
5th Wheel Internal Half Ring	2487	106.4	106.4	52.65	0.043	5.57	1.42	5	40	11
Jam										
Ineff Check Fail Label Press On Gluer	2182	104.7	104.7	54.56	0.048	6.98	1.34	5	47	8

Foil Vs Trigger In Efficiency Always Active	1708	95.7	95.7	56.31	0.056	9.16	1.22	5	56	4
Micro Stoppage	3173	90.7	90.7	57.97	0.029	1.74	1.61	5	14	68
Istjam On Channel	1349	79.8	79.8	59.43	0.059	10.00	1.12	5	56	3
Foil Out Of Possition	1444	78.4	78.4	60.86	0.054	8.69	1.15	5	50	7
No Cigarettes In Feeder X	1699	71.1	71.1	62.16	0.042	5.32	1.22	5	32	15
Hopper Pusher Guard Open	1441	67.7	67.7	63.40	0.047	6.71	1.15	5	39	13
Foil Drum Torque Regulation	1060	61.0	61.0	64.51	0.058	9.57	1.05	5	50	6
Jam 5th Wheel	1456	57.4	57.4	65.56	0.039	4.67	1.15	5	27	25
Upper Packet Top Heater Not Ready	1013	53.2	53.2	66.54	0.053	8.21	1.04	5	42	10
HHS foil Piston limit stem outside	1125	47.4	47.4	67.40	0.042	5.40	1.07	5	29	18
No Label On Gluer	1023	46.8	46.8	68.26	0.046	6.38	1.04	5	33	14

These stoppages directly erode productivity and increase reject rates. "Stop From Cigarette Reserve" interrupts material flow, creating underfilled packs and wasted foils. "Jam on Exit Channel" crushes packets and causes repetitive stoppages, while "Incomplete Cigarette Pocket" leads to substandard bundles requiring full rejection. Lower-priority but frequent events such as "Service Stop" (RPN 18) cumulatively depress line efficiency despite lower individual severity.

4.5.1.2 Failure Modes for Maker Machines

Maker machines form tobacco rods, attach filters, and wrap cigarettes at very high speeds. As the first stage in the Make-Pack line, any defect originating here propagates downstream into Packers and Cellophaners, amplifying reject rates and raw-material waste. Ensuring Maker reliability is therefore fundamental to controlling tobacco and paper losses.

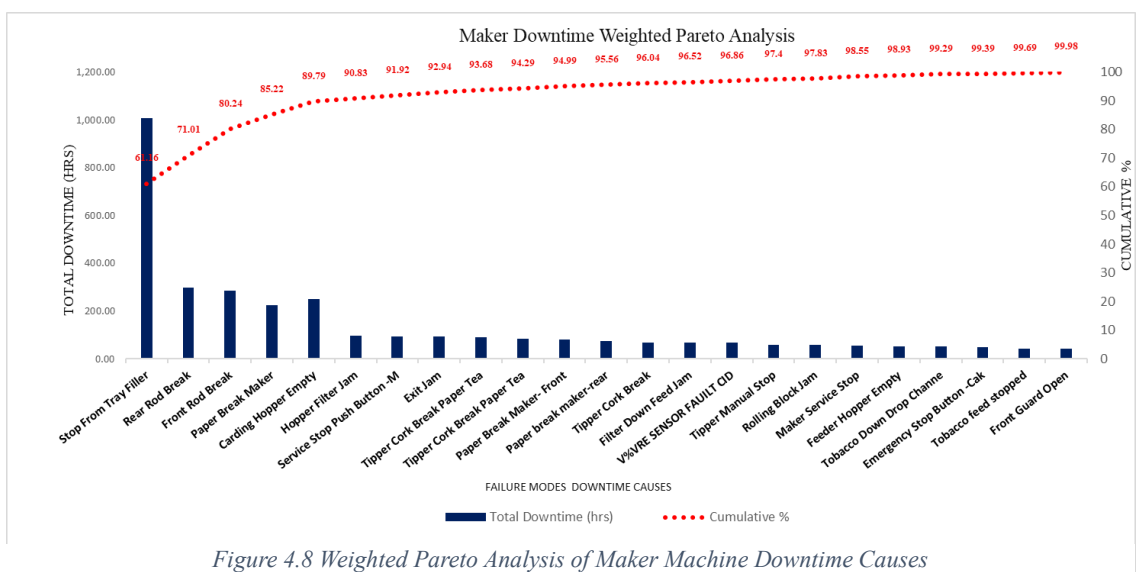


Figure 4.8 Weighted Pareto Analysis of Maker Machine Downtime Causes

The FMEA combined with Weighted Pareto Analysis reveals that a small set of stoppages cause nearly half of total Maker downtime. "Stop From Tray Filler" (RPN 347) is the single most critical mode, followed by "Carding Hopper Empty" (RPN 95), "Rear Rod Break" (RPN 93), and "Front Rod Break" (RPN 89) These stoppages are tightly linked to material waste. "Stop From Tray Filler" interrupts tobacco or filter feed, causing incomplete assembly and scrap. "Carding Hopper Empty" halts production entirely, while "Rear Rod Break" and "Front Rod Break" produce malformed cigarettes requiring rejection lower-priority but frequent stoppages such as "Service Stop Push Button - Maker" (RPN 34) or "Tipper Manual Stop" (RPN 21) reduce OEE even if their direct reject impact is limited

Table 4.11 Failure Modes (Weighted Pareto + FMEA) for Maker Machines

Failure Mode	Freq (w _i)	Total Downtime hrs (x _i ·w _i)	Weighted Downtime	Cumulative %	WAD hrs	Sev	Occ	Det	RPN	Priority
Stop From Tray Filler	8849	1006.4	1006.4	30.55	0.114	6.94	10.00	5	347	1
Rear Rod Break	4806	298.4	298.4	39.61	0.062	3.24	5.74	5	93	3
Front Rod Break	4694	286.5	286.5	48.31	0.061	3.17	5.62	5	89	4
Carding Hopper Empty	2675	248.8	248.8	55.86	0.093	5.45	3.49	5	95	2
Paper Break Maker	3241	223.7	223.7	62.65	0.069	3.74	4.09	5	76	5
Hopper Filter Jam	1563	96.3	96.3	65.57	0.062	3.21	2.32	5	37	10
Service Stop Push Button - Maker	1694	94.2	94.2	68.43	0.056	2.78	2.46	5	34	13
Exit Jam	1585	93.9	93.9	71.29	0.059	3.04	2.34	5	36	11
Tipper Cork Break Paper Tear Photo Cell -2	1177	91.2	91.2	74.05	0.077	4.34	1.91	5	42	7
Tipper Cork Break Paper Tear Photocell-1	1080	82.9	82.9	76.57	0.077	4.29	1.81	5	39	8
Paper Break Maker- Front	1243	82.4	82.4	79.07	0.066	3.54	1.98	5	35	12
Paper break maker-rear	1133	73.2	73.2	81.29	0.065	3.42	1.87	5	32	15
Tipper Cork Break	1011	68.9	68.9	83.39	0.068	3.68	1.74	5	32	16
Filter Down Feed Jam	1006	68.8	68.8	85.47	0.068	3.69	1.73	5	32	14
V%VRE SENSOR FAULT CID	743	67.9	67.9	87.54	0.091	5.34	1.46	5	39	9
Tipper Manual Stop	1317	59.5	59.5	89.34	0.045	2.04	2.06	5	21	18
Rolling Block Jam	1096	57.5	57.5	91.09	0.052	2.56	1.83	5	23	17
Maker Service Stop	1847	56.7	56.7	92.81	0.031	1.00	2.62	5	13	23
Feeder Hopper Empty	1080	51.3	51.3	94.37	0.048	2.20	1.81	5	20	20
Tobacco Down Drop Channel Empty	1018	50.9	50.9	95.91	0.050	2.38	1.75	5	21	19

4.5.1.3 Failure Modes for Cellophaner Machines

Cellophaner machines overwrap cigarette packets with protective film, ensuring moisture resistance and finished-product integrity. Failures here primarily waste non-tobacco materials and generate finished-product rejects, lowering overall yield. The Cellophaner downtime Pareto chart reveals that a small number of failure modes such as "Stop From Cartoner," "Service Stop Button Pressed," and "Ch Spider, Packet Out Of Position" account for the majority of downtime, with the top five contributing over 50% of total losses. This confirms the Pareto Principle, emphasizing that targeted interventions on these "vital few" issues can significantly improve equipment reliability and reduce waste.

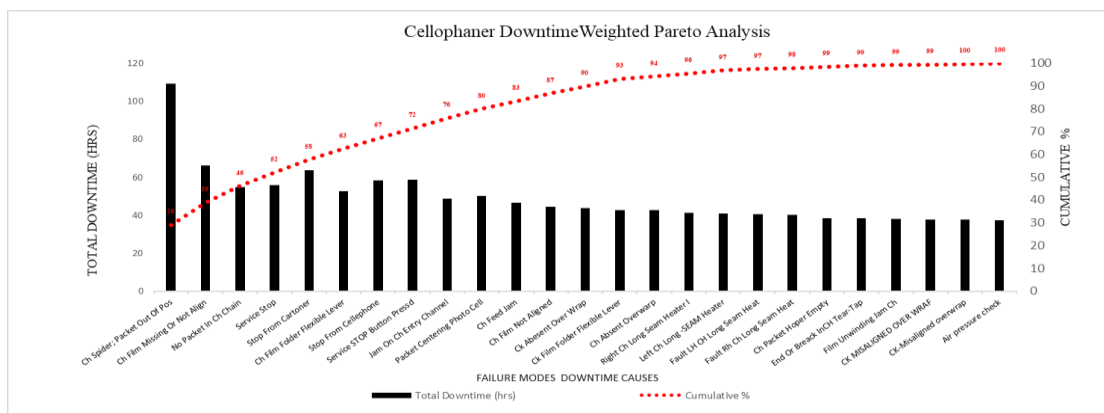


Figure 4.9 Weighted Pareto Analysis of Cellophaner Machine Downtime Causes

The FMEA and Weighted Pareto Analysis identify three dominant stoppages: "Stop From Cartoner" (RPN 87), "Service Stop Button Pressed" (RPN 73), and "Stop From Cellophane" (RPN 72). Together, these account for over 40% of Cellophaner downtime, causing downstream disruption and product rejects.

Table 4.12 Failure Modes (Weighted Pareto + FMEA) for Cellophaner Machines

Failure Mode	Freq (w _i)	Total Downtime hrs (x _i ·w _i)	Weighted Downtime	Cumulative %	WAD hrs	Sev	Occ	Det	RPN	Priority
Ch Spider, Packet Out Of Position	3618	109.2	109.2	8.58	0.030	1.07	10.00	5	53	6
Ch Film Missing Or Not Aligned	2014	66.2	66.2	13.78	0.033	1.97	4.69	5	46	8
Stop From Cartoner	1195	63.5	63.5	18.76	0.053	8.80	1.98	5	87	1
Service sTOP Button Pressed	1035	58.7	58.7	23.37	0.057	10.00	1.45	5	73	2

Stop From Cellephone	1067	58.2	58.2	27.95	0.055	9.27	1.56	5	72	3
Service Stop	1444	55.9	55.9	32.34	0.039	3.94	2.81	5	55	4
No Packet In Ch Chain	1828	54.8	54.8	36.64	0.030	1.00	4.08	5	20	26
Ch Film Folder Flexible Lever	1252	52.7	52.7	40.78	0.042	5.08	2.17	5	55	5
Packet Centering Photo Cell Insufficient	1078	50.1	50.1	44.71	0.046	6.55	1.60	5	52	7
Jam On Ch Entry Channel	1235	48.8	48.8	48.55	0.040	4.21	2.12	5	45	9
Ch Feed Jam	1013	46.7	46.7	52.21	0.046	6.43	1.38	5	44	10
Service Stop, Product Wait	898	44.9	44.9	55.74	0.050	7.74	1.00	5	39	12
Ch Film Not Aligned	1027	44.3	44.3	59.22	0.043	5.43	1.43	5	39	11
Ck Absent Over Wrap	1001	43.6	43.6	62.65	0.044	5.57	1.34	5	37	13
Ck Film Folder Flexible Lever	1010	42.8	42.8	66.01	0.042	5.17	1.37	5	35	14
Ch Absent Overwarp	999	42.6	42.6	69.35	0.043	5.26	1.33	5	35	15
Right Ch Long Seam Heater Not Ready	975	41.2	41.2	72.59	0.042	5.13	1.25	5	32	16
Left Ch Long -SEAM Heater Not Ready	974	41.0	41.0	75.81	0.042	5.08	1.25	5	32	17
Fault LH CH Long Seam Heater Thermostat	968	40.4	40.4	78.98	0.042	4.96	1.23	5	31	18
Fault Rh Ch Long Seam Heater Thermost	967	40.2	40.2	82.14	0.042	4.90	1.23	5	30	19

4.5.2 5 Why Analysis for Critical Downtime Incidents

Root Cause Analysis (RCA) is a systematic diagnostic approach to identify the underlying causes of equipment failures, ensuring corrective measures target systemic issues rather than superficial symptoms. In this study, RCA was applied to the top five critical downtime incidents for each machine type (Maker, Packer, and Cellophaner) identified in Section 4.3.1, based on Failure Mode and Effects Analysis (FMEA) and Weighted Pareto Analysis. The selection criteria prioritized incidents with the highest Risk Priority Number (RPN), longest downtime duration, and greatest impact on reject rates, aligning with the Pareto principle to focus on the "vital few" issues responsible for the majority of operational losses. This analysis directly addresses Research Question 2: "What are the primary causes of production reject at the National Tobacco

Enterprise?" and supports Specific Objective 4: "To evaluate the role of Reliability-Centered Maintenance (RCM) in optimizing equipment performance and minimizing production disruptions."

The following table summarizes the RCA for the top five failure modes across Maker, Packer, and Cellophaner machines, detailing the causal chain (Why 1-5) and the identified root cause for each failure mode.

Table 4.13 5 Why Analysis for Critical Downtime Incidents by Machine

Machine	Failure Mode Description	Why 1?	Why 2?	Why 3?	Why 4?	Why 5?	Root Cause
Maker Machines	Stop From Tray Filler	Because the cigarette feed was interrupted	Because the tray was blocked by residue	Because the cleaning was not done on time	Because the preventive maintenance checklist was not followed	Because the PM audits were not enforced	Lack of preventive cleaning discipline
	Carding Hopper Empty	Because the tobacco feed stopped	Because the sensor failed to detect low level	Because the sensor calibration was overdue	Because the PM was delayed due to workload	Because no automated PM tracking exists	Missed sensor calibration schedule
	Rear Rod Break	Because cigarette rods fractured	Because the paper tension was uneven	Because the tensioner was worn out	Because the spare part was unavailable	Because procurement was delayed	Inefficient spare-part management
	Front Rod Break	Because cigarettes were malformed	Because the rod density control failed	Because the feeder belt slipped	Because the belt was worn out	Because replacement was not planned	Delayed feeder belt replacement
	Tipper Cork Break	Because cigarettes lost tipping alignment	Because the cork drum jammed	Because debris accumulated inside	Because cleaning intervals were skipped	Because operators prioritized output over cleaning	Poor operator adherence to cleaning SOP
Packer Machines	Stop From Cigarette Reserve	Because the cigarette supply at the hopper was depleted	Because upstream Maker did not synchronize	Because the feeder alert did not trigger	Because the sensor was misaligned	Because preventive recalibration was not performed	Inadequate inter-machine sensor control
	Jam on Exit Channel	Because packets were crushed in the exit channel	Because the guide rails were damaged	Because the rails were not replaced in time	Because PM was skipped to meet production targets	Because escalation protocol was missing	Weak preventive maintenance planning
	Incomplete Cigarette Pocket	Because pockets were underfilled	Because Maker misfeeds occurred	Because the tobacco strand moisture was unstable	Because no humidity control room exists	Because QC checks were not enforced	Poor strand moisture management
	Service Stop	Because operators frequently halted the machine	Because downstream misfeeds persisted	Because rollers were dirty	Because cleaning was skipped	Because PM intervals were too long	Unreliable PM schedule and operator discipline
	Repair Mechanical	Because major mechanical breakdowns occurred	Because critical parts wore out	Because there was no predictive monitoring	Because spare parts were stocked out	Because procurement lacked lead-time control	Poor reliability-centered inventory planning
Cellophaner Machines	Stop From Cartoner	Because the cartoner jammed	Because packet	Because transfer	Because adjustment	Because operators	Improper setup and operator

			orientation was wrong	drum was misadjusted	was missed during PM	were not trained	training gaps
	Service Stop Button Pressed	Because operators intervened frequently	Because persistent misfeeds occurred	Because feeder rollers were dirty	Because cleaning was skipped	Because time pressure overrode SOP	Poor PM discipline and operator adherence
	Stop From Cellophane	Because wrapping material feeding failed	Because the tensioner was off-balance	Because calibration was skipped	Because PM intervals were too long	Because SOP compliance was not verified	Inconsistent tensioner calibration
	Film Misalignment	Because film guides shifted	Because mounting bolts were loose	Because torque checks were missed	Because PM was inadequate	Because audit inspections were not done	Weak torque verification procedures
	Repair Electrical	Because power failures halted production	Because wiring degraded over time	Because no thermal inspection was done	Because predictive maintenance was not implemented	Because staff lacked training on early detection	Insufficient predictive electrical maintenance

4.5.3 Fishbone diagram for identified root causes

A Fishbone diagram, also known as an Ishikawa diagram or Cause-and-Effect diagram, is a fundamental analytical tool in industrial engineering used to systematically identify, categorise, and visually represent potential causes contributing to a specific problem. In this study, the Ishikawa diagram was employed to synthesise the root causes uncovered through the 5 Whys Root Cause Analysis (RCA). The analysis targeted the top fifteen critical downtime incidents across the Maker, Packer, and Cellophane machines at the National Tobacco Enterprise (NTE). These causal factors were organised under the 6M framework Machine, Method, Man (People), Material, Measurement, and Environment to provide a structured view of how operational, technical, and organisational elements converge to drive high cigarette production waste and downtime within the Make-Pack department. This visual tool was used not only to consolidate RCA findings but also to guide the prioritisation of corrective actions by clearly linking observed effects to their underlying causes.

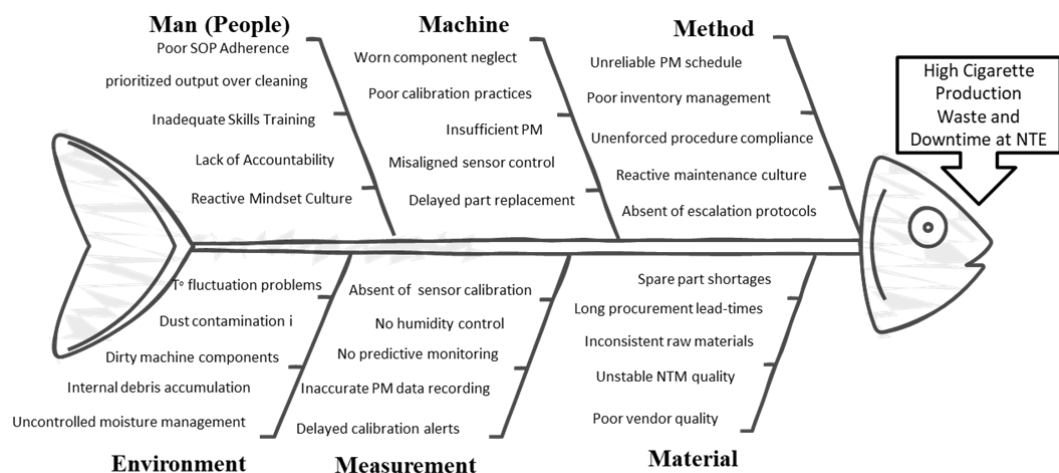


Figure 4.10 Fishbone Diagram for Identified Root

4.6 Qualitative Findings

This section synthesizes insights from semi-structured interviews, focus groups, and the structured employee survey analyzed using SPSS. The combined evidence highlights how operator practices, maintenance culture, and Lean implementation influence machine reliability and waste reduction within the Make-Pack department.

Table 4.14 Demographic Profile of Survey Respondents

Characteristic	Category	Frequency (n = 39)	Percentage (%)
Job Title	Operator	26	66.7%
	Technician (Mechanic + Electrician)	9	23.1%
	Supervisor/ (Shift + Maintenance)	4	10.2%
Tenure	< 2 years	13	33.3%
	2-5 years	26	66.7%

4.6.1 Thematic Analysis of Interviews & Focus Groups

Interviews and focus groups revealed a shared understanding of different forms of production waste, including visible rejects, waiting losses, and unplanned downtime. Maintenance activities were described as predominantly reactive, with insufficient operator participation in preventive tasks. Communication gaps between production and maintenance staff were frequently cited as barriers to timely problem resolution, and training on Lean tools, troubleshooting, and reliability-centered maintenance was noted as inconsistent. Although employees are aware of Lean practices such as 5S, Kaizen, and standard work, these initiatives are often perceived as management-driven rather than embedded in daily routines, limiting long-term impact.

4.6.2 Reliability and Validity Correlation Analysis

Survey constructs Continuous Improvement (CI), Operational Performance (OP), Process Management (PM), Machine Reliability (MR), Autonomous Maintenance (AM), and Lean implementation demonstrated excellent internal consistency (Cronbach's $\alpha = 0.979$) and strong intercorrelations ($r = 0.83-0.97$, $p < 0.01$), confirming measurement reliability. Mean scores ranged from 3.36 to 3.66 on a five-point scale, with Lean implementation (3.55) and machine reliability (3.66) slightly higher than other areas. One-way ANOVA revealed significant differences in

perceptions by tenure and job title ($p < 0.05$), indicating that frontline operators and senior staff assess Lean practices and maintenance responsibilities differently. High correlations between machine reliability and autonomous maintenance ($r = 0.91$) support qualitative findings that empowering operators with preventive maintenance skills could reduce unplanned stoppages. Similarly, the strong association between continuous improvement and Lean ($r = 0.94$) aligns with feedback that improvement meetings lack systematic follow-up

Table 4.15 Statistical Findings Integrated with Field Insights

Construct	Mean (SD)	Key Statistical Findings	Supporting Qualitative Evidence
Continuous Improvement	3.36 (0.78)	$\alpha = 0.979$, strong R with OP (0.95) and Lean (0.94), tenure effect $p < 0.05$	Weak follow-up on employee suggestions and insufficient structured training
Operational Performance	3.49 (0.80)	R with Lean 0.97, significant job-title effect $p < 0.01$	Unclear performance metrics and slow feedback mechanisms
Process Management	3.40 (0.87)	R with AM 0.87, MR 0.83, tenure effect $p < 0.05$	Inconsistent process documentation and audit practices
Machine Reliability	3.66 (1.04)	R with AM 0.91, CI 0.86, tenure effect $p < 0.05$	Frequent breakdowns and inadequate preventive maintenance
Autonomous Maintenance	3.51 (0.94)	R with Lean 0.97, borderline job-title effect $p \approx 0.06$	Low operator ownership of routine checks and limited technical training
Lean Implementation	3.55 (0.91)	$R > 0.88$ with all constructs, tenure effect $p < 0.05$	Awareness exists but practices are inconsistently applied

These results, summarized in Table 4.15, integrate statistical findings with field insights, showing that while Lean awareness exists, execution is inconsistent due to skill gaps, limited ownership at operator level, and weak feedback loops. Strengthening operator training, embedding standard work, and fostering cross-functional collaboration are essential to improving reliability and minimizing production waste.

4.7 Comprehensive Insights from Value Stream Mapping and Integrated Analysis

This section integrates Value Stream Mapping (VSM) results with the quantitative performance indicators, equipment reliability assessments, and qualitative insights previously discussed, providing a consolidated diagnosis of operational inefficiencies in the Make-Pack department of the National Tobacco Enterprise (NTE). Drawing on field observations, historical cycle-time and uptime data, process records, and operator feedback, the current-state VSM (Figure 4.8) mapped eleven sequential production steps, with detailed metrics presented in this Table.

Table 4.16 Current-State VSM Metrics in the Make-Pack Department

#	Process Step	Cycle Time (CT)	Changeover Time (C/T)	Uptime %	Lead Time per Step (sec)	Proportional LT (%)
1	Request & Stage NTMs	60	60	95%	63	3.75%
2	Delivery of CFTs to Line	30	30	96%	31	1.85%
3	Manual Filter and Tobacco Feeder to Cigarette Maker	165	225	38.5%	908	54.05%
4	Inline Quality Inspection	45	45	90%	50	2.98%
5	Transfer to Cigarette Packer	20	20	92%	22	1.31%
6	Cigarette Packing	90	150	41.2%	578	34.40%
7	Cellophane Sealing	60	90	39.6%	152	9.05%
8	Bundling Filling into Shipping Cases	105	120	89%	358	21.31%
9	Sealing & Labelling	30	30	93%	32	1.90%
10	Manual Palletisation	90	90	92%	278	16.55%
11	Transport to FG Warehouse	30	30	95%	32	1.90%
	Total				1,680	100%

The VSM visually confirmed that these process disruptions aligned with waste categories defined in Lean methodology, particularly waiting waste and defect propagation. Rather than isolated inefficiencies, the flow instability was driven by underlying machine reliability problems, providing an empirical foundation for the subsequent integrated analysis.

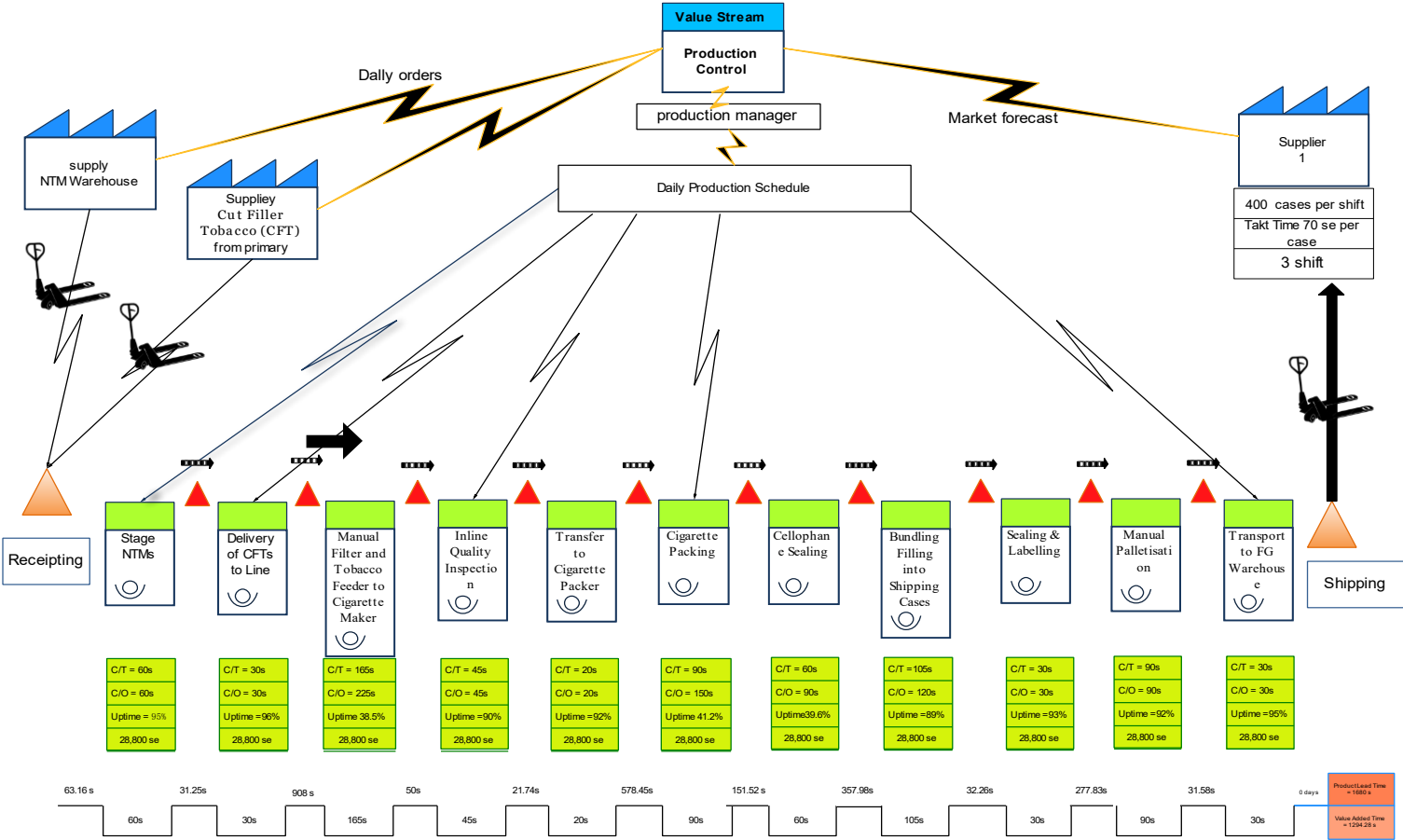


Figure 4.11 Current-State Value Stream Map for the Make-Pack Department

4.7.1 Current-State VSM Insights

The VSM revealed stable upstream processes such as Non-Tobacco Material (NTM) staging (Cycle Time: 60 s, Uptime: 95%) and Cigarette Filter Tip delivery (Cycle Time: 30 s, Uptime: 96%), which showed minimal disruption and negligible work-in-process accumulation. However, critical bottlenecks were concentrated in midstream and downstream operations. The manual filter and tobacco feeding to the cigarette maker exhibited a cycle time of 165 s and only 38.5% uptime, accounting for more than half of the total proportional lead time. Cigarette packing (Cycle Time: 90 s, Uptime: 41.2%) and cellophane sealing (Cycle Time: 60 s, Uptime: 39.6%) presented similar constraints. These low-uptime stages disrupted flow, created upstream accumulation, left downstream stations underutilized, and extended the department's total lead time to 1,680s.

4.7.2 Integrated Analysis of Operational Bottlenecks and Reliability Metrics

Linking VSM findings with quantitative KPIs and reliability assessments reveals a tightly interdependent system where equipment unreliability drives process bottlenecks, high reject rates, and material losses. NTE recorded an average cigarette reject rate of 5.0193% against a 3.20% target and NTM waste of 3.3833% against a 1.00% target (Table 4.1), alongside an OEE of only 35.8550% compared to a target of 43.90%. Regression analysis showed that OEE explained 50.8% of reject rate variability and 78.1% of NTM yield variability, confirming that improved equipment performance directly reduces waste.

The bottleneck stages identified by the VSM correspond precisely to dominant failure modes highlighted by FMEA and Root Cause Analysis. In the cigarette maker, uptime losses (38.5%) were traced to "Stop From Tray Filler" (RPN 347) and "Carding Hopper Empty" (RPN 95), caused by missed sensor calibration and poor preventive cleaning discipline. In the packer (41.2% uptime), failures such as "Stop From Cigarette Reserve" (RPN 146) and "Jam on Exit Channel" (RPN 68) stemmed from inadequate sensor control and weak preventive maintenance planning. In the cellophaner (39.6% uptime), downtime due to "Stop From Cartoner" (RPN 87) and "Service Stop Button Pressed" (RPN 73) was linked to improper setup, operator training gaps, and poor adherence to preventive maintenance schedules.

These technical findings were supported by qualitative data from interviews and focus groups (Cronbach $\alpha = 0.979$), which described a predominantly reactive maintenance culture, insufficient operator involvement in preventive tasks, and inconsistent application of Lean tools such as 5S and Kaizen. The table below consolidates the relationships among process steps, performance losses, dominant failure modes, and systemic root causes.

4.8 Summary of Key Findings

The data analysis at the National Tobacco Enterprise's (NTE) Make-Pack department reveals a chronic state of operational underperformance and high production waste, consistently exceeding internal targets and global industry standards. Quantitative findings demonstrated statistically significant deviations with cigarette reject rates averaging 5.0193% (versus a 3% target) and Non-Tobacco Material (NTM) waste rates averaging 3.3833% (versus a 1% target). Concurrently, Overall Equipment Effectiveness (OEE) significantly underperformed, averaging 35.8550% against a 43.9% target, and Production Yield consistently fell short of its 94% target, averaging 89.3977%. Linear regression analysis empirically established OEE as a critical independent variable, explaining approximately 50.8% of the variability in reject rates and 78.1% in NTM yield, thereby confirming that equipment unreliability is a primary driver of production waste. Equipment reliability assessments, combining Failure Mode and Effects Analysis (FMEA) and Root Cause Analysis (RCA), pinpointed key failure modes across Maker, Packer, and Cellophaner machines, such as "Stop From Cigarette Reserve" and "Stop From Tray Filler," with root causes including lack of preventive cleaning discipline, inefficient spare-part management, inadequate inter-machine sensor control, weak preventive maintenance planning, and operator training gaps. Complementary qualitative insights from interviews, focus groups, and Value Stream Mapping highlighted a predominantly reactive maintenance culture, communication deficits, inconsistent Lean tool implementation perceived as management-driven, and significant bottlenecks in critical midstream processes like manual feeding and packing due to low uptime.

Chapter Five

Discussion

5.1 Introduction

This chapter interprets the empirical results presented in Chapter 4, which documented persistent underperformance in NTE's Make-Pack line. Specifically, the mean cigarette reject rate was approximately 5.02% (target 3.20%), mean NTM waste approximated 3.38% (target 1.00%), and mean OEE stood at around 35.86% (target 43.90%), major bottlenecks were identified at the Maker, Packer, and Cellophaner stages (see Table 4.16 and Figure 4.8).this chapter interprets these findings in relation to this study research questions, compares them with prior literature on Lean manufacturing and Reliability-Centered Maintenance (RCM), explains observed patterns, and derives both practical and theoretical implications.the discussion proceeds by interpreting findings against research questions, comparing them with previous studies, synthesising an integrated Lean-RCM framework, outlining practical and theoretical implications, reflecting on methodological aspects, and identifying academic contributions and avenues for future research.

5.2 Interpretation of Findings in Relation to Research Questions

This section provides an in-depth interpretation of the empirical findings from Chapter 4, directly addressing this study research questions and objectives. Each subsection summarises key evidence, links it to relevant Lean manufacturing and RCM theory, elucidates observed patterns, and concludes with its significance for NTE and the broader industrial context.

5.2.1 Deviations in Production Waste and Efficiency (Rejects, NTM, OEE)

This subsection presents the magnitudes and trends of production waste and operational efficiency at NTE, providing critical empirical evidence that underpins this study formal research questions regarding the primary causes of production reject and the optimization of production processes. chapter 4 documented significant and statistically confirmed deviations from target performance in key operational metrics at NTE. Specifically, the mean cigarette reject rate averaged 5.0193%, which was significantly

higher than the 3.20% target ($t(29) = 6.518, p < .001$). Non-Tobacco Material (NTM) waste averaged 3.3833%, also considerably above the 1.00% target ($t(29) = 8.697, p < .001$). concurrently, Overall Equipment Effectiveness (OEE) averaged 35.8550%, significantly below the 43.90% target ($t(29) = -8.235, p < .001$). production yield, another critical efficiency metric, averaged 89.3977%, falling short of its 94.00% target ($t(29) = -8.916, p < .001$). these quantitative results, supported by data in Table 4.1 (Descriptive Statistics), Table 4.2 (Cigarette Reject Rate), Table 4.3 (Paired Samples Test for NTM Waste Rate), Table 4.4 (Paired Samples Test for OEE), Table 4.8 (Production yield Paired Samples Test), Figure 4.2 (Trend of Cigarette Reject Rate (%)), Figure 4.3 (Trend of NTM Waste Rate (%)), Figure 4.4 (Monthly NTM yield Percentages (2022-2024) vs. target), Figure 4.5 (Overall Equipment Effectiveness (OEE) (%) (2022-2024)), and Figure 4.6 (Production yield (2022-2024)), consistently underscore a chronic state of operational underperformance within NTE's Make-Pack department.

Operationally, these numbers translate into substantial losses for NTE. A 5% cigarette reject rate means that for every 100 cigarettes produced, five are discarded due to quality failures, incurring direct costs from wasted tobacco and packaging materials, as well as indirect costs from reprocessing or disposal. Similarly, the 3.38% NTM waste rate signifies inefficient utilisation of imported packaging materials, contributing to higher operational costs and an increased environmental footprint. the consistently low OEE of 35.9% indicates significant underutilisation of equipment capacity due to chronic issues with availability (downtime), performance (speed losses), and quality (defects). Such low OEE levels directly impede production output and profitability, leading to capacity shortfalls and extended lead times. the persistent shortfall in Production yield further confirms these operational inefficiencies, demonstrating NTE's struggle to achieve planned output consistently, impacting market supply and revenue generation.

In the context of Lean manufacturing theory, these findings are clear signatures of systemic waste. the elevated reject rates are a direct manifestation of the Lean waste category of 'Defects', indicating process instability and quality control shortcomings, consistent with Womack & Jones-style framing (Womack & Jones, 1997). the low OEE, driven by frequent machine breakdowns and stoppages, points to significant 'Waiting'

waste, where production halts due to unreliable equipment. Furthermore, the high NTM waste reflects issues related to 'Over-processing' or 'Scrap' due to inefficient material handling and packaging defects. The observed seasonality in reject rates, OEE, and production yield with declines often at the start and end of the year suggests underlying problems with machine maintenance, inconsistent resource utilisation, or external factors like raw material quality. Qualitative insights from employee feedback indirectly support this by highlighting a predominantly reactive maintenance culture and inconsistent application of Lean tools.

These results unequivocally support the hypothesis that chronic equipment unreliability is profoundly associated with elevated waste and low operational efficiency.

5.2.2 Reliability Failures and Root Causes (FMEA + RCA interpretation)

Addressing the research question, "What equipment failure modes and root causes drive downtime and waste?", Chapter 4's Equipment Reliability Assessment, utilising FMEA and Root Cause Analysis (RCA), pinpointed specific high-impact failure modes and their underlying causes across the Maker, Packer, and Cellophaner machines.

For Packer machines (see **Table 4.10**), "Stop From Cigarette Reserve" (RPN 146) was identified as the most critical failure mode, contributing significantly to downtime and waste. This stoppage directly interrupts the material flow, creating underfilled packs and wasted foils. RCA traced this to inadequate inter-machine sensor control and a missed preventive recalibration schedule. Other critical Packer failures included "Jam on Exit Channel" (RPN 68), which crushes packets, and "Incomplete Cigarette Pocket" (RPN 51), resulting in substandard bundles and rejections. These were linked to weak preventive maintenance planning (damaged guide rails not replaced, PM skipped to meet production targets) and poor strand moisture management (unstable tobacco strand moisture leading to misfeeds, no humidity control), respectively. Frequent 'Service Stops' by operators (RPN 18) were further attributed to an unreliable PM schedule and poor operator discipline (PM intervals too long, cleaning skipped).

On the Maker machines (see **Table 4.11**), the single most critical failure mode was "Stop From Tray Filler" (RPN 347), causing nearly a third of total Maker downtime. This directly leads to incomplete assembly and scrap due to interrupted tobacco or filter feed. RCA revealed the root cause as a lack of preventive cleaning discipline and unenforced

PM audits (cleaning not done on time, PM checklist not followed, PM audits not enforced). "Carding Hopper Empty" (RPN 95), which halts production entirely, was caused by a missed sensor calibration schedule (sensor calibration overdue, PM delayed due to workload, no automated PM tracking). Other significant failures, "Rear Rod Break" (RPN 93) and "Front Rod Break" (RPN 89), resulting in malformed cigarettes, were attributed to inefficient spare-part management (spare part unavailable, procurement delayed) and delayed feeder belt replacement (feeder belt slipped, belt worn out, replacement not planned), highlighting supply chain and planned maintenance deficiencies.

For Cellophaner machines (see Table 4.12), the dominant stoppages included "Stop From Cartoner" (RPN 87), "Service Stop Button Pressed" (RPN 73), and "Stop From Cellophane" (RPN 72). collectively, these accounted for over 40% of Cellophaner downtime, causing downstream disruption and product rejects. RCA linked "Stop From Cartoner" to improper setup and operator training gaps (packet orientation wrong, transfer drum misadjusted, adjustment missed during PM, operators not trained). "Service Stop Button Pressed" was linked to poor PM discipline and operator adherence (persistent misfeeds, feeder rollers dirty, cleaning skipped, time pressure overrode SOP). "Stop From Cellophane" was attributed to inconsistent tensioner calibration (tensioner off-balance, calibration skipped, PM intervals too long, SOP compliance not verified). Issues like "Film Misalignment" were traced to weak torque verification procedures and inadequate PM.

These findings align with Reliability-Centered Maintenance (RCM) theory, which advocates for maintenance strategies based on failure modes and their impact. Many identified root causes such as missed PM, sensor miscalibration, spare-part management issues, and operator training gaps point to wear-out related failures or human-induced errors that are amenable to RCM interventions (Alrifayy et al., 2020). For instance, missed calibrations suggest a need for scheduled maintenance or predictive monitoring, while spare-part delays call for optimised inventory strategies. The high RPNs, especially for "Stop From Tray Filler" (RPN 347), underscore the unusually severe impact of reliability failures at NTE compared to industry benchmarks, likely exacerbated by a predominantly reactive maintenance culture and insufficient operator involvement in preventive tasks, as described in qualitative

findings. this deep dive into FMEA and RCA explicitly identifies a small, critical set of high-impact failure modes and their systemic root causes as the primary drivers of NTE's observed KPI shortfalls.

5.2.3 Bottlenecks and Flow Disruptions (VSM Insights)

This section contributes to addressing this study research objectives by investigating where in the process flow constraints occur and how they relate to waste and reliability, an inquiry critical for understanding the primary causes of production reject and for optimizing production processes at NTE. the Value Stream Mapping (VSM) conducted in Chapter 4 provided a visual and quantitative representation of material and information flow within NTE's Make-Pack department, clearly identifying critical bottlenecks and flow disruptions.

The VSM results, detailed in **Table 4.16** (Current-State VSM Metrics for the Make-Pack Department) and visually represented in **Figure 4.8** (Current-State VSM), revealed that while upstream processes like Non-Tobacco Material (NTM) staging (Cycle Time (CT): 60s, Uptime: 95%) and Cigarette Filter Tip (CFT) delivery (CT: 30s, Uptime: 96%) exhibited minimal disruption, significant inefficiencies were concentrated in midstream and downstream operations. the most pronounced bottleneck was at the Manual Filter and Tobacco Feeder to Cigarette Maker stage, which had a prolonged cycle time of 165s and a critically low uptime of 38.5%, accounting for over half (54.05%) of the total proportional lead time. Similar constraints were evident in Cigarette Packing (CT: 90s, Uptime: 41.2%, Proportional Lead Time: 34.40%) and Cellophane Sealing (CT: 60s, Uptime: 39.6%, Proportional Lead Time: 9.05%). these low-uptime stages severely disrupted the entire value stream, leading to material accumulation upstream, underutilised downstream stations, and an extended total departmental lead time of 1,680s.

The flow logic interpreted from these VSM metrics indicates a clear violation of production takt time and the generation of significant work-in-process (WIP) and 'Waiting' waste. For example, the Maker's feeding stage, consuming over 50% of the lead time with low uptime, creates frequent starvation for downstream machines or overaccumulation of WIP upstream, destabilising the entire line. this instability

propagates defects, as operators may rush or bypass quality checks during recovery periods, further exacerbating the 'Defects' waste category.

Crucially, the VSM insights directly link to the reliability failures identified in Section 5.2.2. the low uptime at the Maker (38.5%) is a direct consequence of high-RPN failure modes such as "Stop From Tray Filler" (RPN 347) and "Carding Hopper Empty" (RPN 95), which were traced to root causes like missed sensor calibration and poor preventive cleaning discipline. Similarly, the Packer's low uptime (41.2%) stems from "Stop From Cigarette Reserve" (RPN 146) and "Jam on Exit Channel" (RPN 68), resulting from inadequate sensor control and weak preventive maintenance planning. the Cellophaner's uptime (39.6%) is compromised by failures like "Stop From Cartoner" (RPN 87) and "Service Stop Button Pressed" (RPN 73), linked to improper setup, operator training gaps, and poor adherence to PM schedules. these operational manifestations confirm that the most critical flow constraints are indeed symptoms of chronic equipment unreliability.

The VSM evidence comprehensively answers the research question about flow constraints by identifying and quantifying the location and mechanisms of bottlenecks within the Make-Pack department. It demonstrates that process disruptions are not isolated inefficiencies but rather symptoms of underlying machine reliability problems, providing a strong empirical foundation for an integrated Lean and RCM response.

5.3 Comparison with Previous Studies

This section positions NTE's findings within the broader academic literature on Lean manufacturing and Reliability-Centered Maintenance, articulating where the study confirms, extends, or diverges from existing knowledge.

5.3.1 Production Waste and Efficiency in Context of Lean Literature

The magnitude and patterns of production waste and operational inefficiency observed at NTE largely align with challenges documented in the Lean literature, particularly in contexts where Lean principles are not fully integrated or consistently applied. NTE's mean cigarette reject rate of 5.02% significantly exceeds both its internal targets (3.2%) and global industry benchmarks (2-3%) achieved by companies employing Lean practices. Similarly, the average OEE of 35.86% falls considerably below the target of

43.90%.these figures indicate substantial 'Defects' and 'Waiting ' waste, which are core areas of focus for Lean interventions ([Womack & Jones, 1997](#)).

Previous studies have consistently shown the effectiveness of Lean tools in reducing waste and improving efficiency. For instance, [Indrawati et al. \(2019\)](#) documented significant waste reductions in a steel plant through layout redesign and 5S methodology, while [Dinesh et al. \(2022\)](#) reported a 15% reduction in work-in-process inventory in carton production using Value Stream Mapping (VSM). [Syahputri et al. \(2018\)](#) demonstrated that Lean tools specifically reduced packaging defects and minimised leaf spoilage in the tobacco industry, and that Lean Six Sigma techniques led to a 12% reduction in defect rates in cigarette paper production. NTE's high reject and NTM waste rates, therefore, strongly contradict the potential benefits achievable through well-implemented Lean practices.

The divergences in NTE's performance can be attributed to several contextual factors highlighted.the problem statement notes that "current maintenance practices and process workflows at NTE are not enough to solve these problems". Qualitative findings indicate a key factor is the inconsistent application of Lean tools, which are "often perceived as management-driven rather than embedded in daily routines".this suggests a gap in organisational culture and employee engagement, a critical component for Lean success ([Grewal, 2008](#)). Furthermore, root causes like poor operator adherence to cleaning SOPs and training gaps contribute to defects, aligning with Lean propositions that a lack of standardised work and underutilised talent increase defect rates and process instability ([Azadeh et al., 2017](#)).

This study confirms the general Lean proposition that unaddressed waste categories lead to significant operational inefficiencies. However, it extends the understanding by highlighting that in resource-intensive and highly regulated sectors like tobacco manufacturing, the inherent complexity and unique challenges (e.g., dust accumulation, sensitive materials) amplify the negative impact of inconsistent Lean implementation, necessitating a more robust, integrated approach.

5.3.2 Reliability Failures and RCM Patterns in Prior Research

The patterns of reliability failures and their impact on waste at NTE demonstrate both alignment with and significant divergence from prior RCM research, particularly within

the process and packaging sectors. The FMEA and RCA results at NTE identified prevalent failure modes linked to missed preventive maintenance (PM), sensor miscalibration, inefficient spare-part management, and operator training gaps. These root causes frequently point to wear-out related failures or human-induced errors that are amenable to RCM interventions (Alrifayy et al., 2020).

RCM literature consistently demonstrates that structured maintenance approaches enhance equipment effectiveness and reduce downtime. Khasanah et al. (2021) showed that applying RCM in process industries significantly improved plant availability and reduced downtime losses. Similarly, Jeon et al. (2020) utilised FMEA to assess failure modes in tobacco rolling and cutting machines, identifying critical components contributing to stoppages. NTE's findings, particularly the prevalence of issues like "Stop From Tray Filler" (RPN 347) and "Stop From Cigarette Reserve" (RPN 146), which are unusually high, indicate a substantial gap in existing PM discipline and reliability engineering practices. This contrasts sharply with successful RCM implementations that prioritise maintenance tasks based on their impact, thereby mitigating such high-risk failures.

The observed scale of high-RPN events at NTE, and their direct linkage to fundamental issues such as lack of preventive cleaning, inadequate sensor control, and poor spare-part lead-time management, aligns with the literature's emphasis on contextual factors explaining divergences (Latinovic et al., 2020; Ali et al., 2019). The qualitative data further supports this, describing a "predominantly reactive maintenance culture" and "insufficient operator involvement in preventive tasks". This reactive approach directly exacerbates issues that RCM aims to prevent, creating an environment where failures become the norm rather than exceptions.

This study adds to the RCM literature by illustrating the severe consequences of neglecting foundational RCM principles in a high-volume, regulated manufacturing environment in a developing economy. It empirically demonstrates that in contexts where Lean practices are weak and maintenance is predominantly reactive, the potential gains from a robust RCM implementation are likely to be far greater, as reliability improvements will yield significant reductions in both waste and operational costs. The

NTE case underscores the critical synergy required between maintenance planning and Lean flow management to achieve operational excellence.

5.3.3 Bottlenecks, Flow, and VSM Applications in Similar Studies

The VSM findings at NTE, pinpointing critical bottlenecks at the Maker, Packer, and Cellophaner stages due to low uptime, confirm the utility of VSM as a diagnostic tool in identifying flow constraints. This aligns with numerous published VSM studies across high-volume manufacturing sectors. For instance, [Aksar et al. \(2022\)](#) demonstrated VSM's effectiveness in reducing lead time and enhancing process flow in the Turkish automotive industry. Similarly, [Dinesh et al. \(2022\)](#) applied VSM in carton production to successfully reduce work-in-process (WIP) inventory by 15%, and [Dewi et al. \(2021\)](#) showed VSM improving lead time efficiency in electronics manufacturing. These studies underscore VSM's capacity to visualise inefficiencies and guide process improvements.

However, a key methodological difference and contribution of the NTE study lies in its explicit integration of VSM findings with quantified reliability failures and Key Performance Indicators (KPIs). Most VSM studies tend to identify bottlenecks but often stop short of systematically linking these to the underlying causes of equipment unreliability and their precise impact on overall operational metrics. The NTE study advances this by demonstrating a tightly interdependent system where the observed VSM bottlenecks (e.g., Maker feeding with 38.5% uptime) were directly caused by dominant failure modes (e.g., "Stop From Tray Filler" with RPN 347) and their root causes (e.g., missed sensor calibration and poor preventive cleaning discipline). Furthermore, this linkage was quantitatively reinforced by regression analysis, which showed OEE (a direct measure of equipment reliability at these bottlenecks) explaining a significant portion of reject rate and NTM yield variability.

This study therefore fits within the literature by confirming the foundational utility of VSM in identifying process flow inefficiencies. However, it significantly advances VSM application by triangulating its insights with FMEA, RCA, and KPI regression analysis. This comprehensive approach moves beyond mere identification to establish a robust empirical link between process bottlenecks, equipment reliability failures, and overall waste generation, thereby providing a more holistic and actionable diagnosis. This integrated perspective is particularly valuable in complex, capital-

intensive environments like tobacco manufacturing, where process stability is intrinsically linked to machine dependability.

5.4 Towards an Integrated Lean-RCM Framework

The findings from NTE underscore that traditional Lean or RCM interventions, applied in isolation, are insufficient to address the systemic operational inefficiencies observed. Instead, a synergistic approach is required, leading to the development of an integrated Lean-RCM framework. This section synthesises the empirical evidence to propose such a model, demonstrating how Lean waste categories are linked to reliability failures and detailing the combined impact on performance.

5.4.1 Linking Lean Waste Categories with Reliability Failures

The analysis at NTE empirically demonstrates a clear and tangible link between traditional Lean waste categories and specific equipment reliability failures. The integration of VSM, FMEA, and RCA highlights how reliability failures are not isolated technical issues but direct drivers of various forms of Lean waste. **Table 5.1** (Key Wastes, Bottlenecks, and Reliability Links in the Make-Pack Line) provides a concise mapping of these interdependencies.

Table 5.1 Key Wastes, Bottlenecks, and Reliability Links in the Make-Pack Line

Process Step	KPI Impact (Reject/OEE/Yield)	Dominant Waste Type	High-RPN Failure Modes	Root Cause Summary
Maker Feeding	Reject increased, OEE decreased	Waiting, Defects, Inventory	Tray Filler Stop (347), Hopper Empty (95)	Missed PM, sensor mis-calibration, training gaps
Cigarette Packing	NTM Waste increased, OEE decreased	Rework, Scrap, Overprocessing	Cigarette Reserve Stop (146), Exit Jam (68)	Setup misalignment, worn parts, poor SOPs
Cellophane Sealing	Yield decreased, OEE decreased	Waiting, Material Scrap	Cartoner Stop (87), Service Stop (73)	Setup error, film handling wear, spare-part delays

Maker Feeding experiences 'Waiting' and 'Defects' due to low OEE and frequent stoppages. The dominant high-RPN failure modes, such as "Stop From Tray Filler" (RPN 347) and "Carding Hopper Empty" (RPN 95), directly cause these wastes. The causal mechanisms here are clear: missed preventive maintenance (PM) and sensor mis-calibration lead to unplanned stops, resulting in machine waiting and the production of defective products.

Cigarette Packing is plagued by 'NTM Waste' and 'Rework', stemming from low OEE and quality issues. Failures like "Stop From Cigarette Reserve" (RPN 146) and "Jam on Exit Channel" (RPN 68) are key culprits. Here, setup misalignment, worn parts, and poor Standard Operating Procedures (SOPs) (e.g., weak PM planning and inadequate sensor control) cause physical damage to packaging materials and necessitate rework, generating considerable scrap and overprocessing waste.

Cellophane Sealing exhibits reduced 'Yield' and 'Material Scrap' due to low OEE. High-RPN failures such as "Stop From Cartoner" (RPN 87) and "Service Stop Button Pressed" (RPN 73) are responsible. The underlying causes, including improper setup, film handling wear, and spare-part delays, directly lead to wrapping material feeding failures and misaligned films, resulting in wasted packaging materials and finished product rejects.

Qualitative findings from interviews and focus groups further illustrate these causal mechanisms. Operators frequently "prioritized output over cleaning" and there was "poor operator adherence to cleaning SOP", directly causing debris accumulation and jams. Similarly, the observation that "operators frequently halted the machine because downstream misfeeds persisted" highlights how upstream reliability failures propagate 'Waiting' waste downstream. This demonstrates that reliability failures are not just technical problems, they fundamentally underpin various forms of Lean waste, highlighting the necessity of an integrated approach.

5.4.2 Combined Impact on OEE, Reject Rate, and NTM Waste

The empirical data from Section 4.4 (Quantitative Findings) provides robust evidence of the combined impact of operational efficiency and reliability on production waste, legitimising joint Lean-RCM interventions. Linear regression analysis clearly

established Overall Equipment Effectiveness (OEE) as a critical independent variable influencing waste generation.

Specifically, the regression results indicate that OEE explains approximately 50.8% of the observed variability in cigarette reject rates ($R^2 = 0.508$, $F(1, 28) = 28.885$, $p < 0.001$) as shown in Table 4.6 (Regression Analysis Summary for Reject Rate (%)).the unstandardised coefficient of 0.203 ($p < 0.001$) implies that each one-percentage-point improvement in OEE is associated with an expected reduction of approximately 0.20 percentage points in the cigarette reject rate.this suggests a direct inverse relationship where enhanced equipment availability, performance, and quality lead to fewer defects.

Even more significantly, OEE demonstrated a strong explanatory power for Non-Tobacco Material (NTM) yield, accounting for 78.1% of its variability ($R^2 = 0.781$, $F(1, 28) = 100.025$, $p < 0.001$) as shown in Table 4.7 (Regression Analysis Summary for NTM yield (%)).the unstandardised coefficient of +0.230 ($p < 0.001$) indicates that for every one-percentage-point improvement in OEE, NTM yield is expected to increase by roughly 0.23 percentage points.this strong positive correlation highlights that stable machine performance directly translates into better material utilisation and reduced packaging waste.

To illustrate this impact, consider a scenario where NTE successfully implements reliability improvements that lead to a 5 percentage point increase in OEE from its current average of 35.86%. Based on the regression coefficients:

- ✚ The cigarette reject rate could be expected to decrease by approximately 1 percentage point (5 percentage points OEE improvement * 0.20 coefficient = 1 percentage point reduction).
- ✚ NTM yield could be expected to increase by approximately 1.15 percentage points (5 percentage points OEE improvement * 0.23 coefficient = 1.15 percentage points increase), leading to a corresponding reduction in NTM waste.

These empirical links provide compelling evidence that chronic equipment unreliability is indeed a primary driver of both high cigarette reject rates and low NTM yield.therefore, joint Lean-RCM interventions are not merely complementary, they are essential for achieving measurable improvements in quality, material utilisation, and

overall operational efficiency at NTE. Strengthening reliability-centered maintenance strategies directly translates into achieving core Lean objectives of waste elimination.

5.5 Proposed Integration Model for NTE

Based on the integrated analysis, a conceptual Lean-RCM integration model is proposed for NTE to systematically address the identified production waste and operational inefficiencies. This model is designed to leverage the strengths of both methodologies, ensuring process efficiency through Lean and equipment stability through RCM, drawing on principles from the "Lean Reliability: A Holistic Optimisation Framework".

The proposed model comprises three interconnected components: Integrated Diagnostics, Synergistic Interventions, and Performance Governance. This structure aligns with the comprehensive "Lean Reliability: A Holistic Optimisation Framework," which aims for a holistic approach to waste reduction, efficiency improvement, and system reliability by treating Lean and Reliability as intertwined elements.

✚ **Integrated Diagnostics:** This phase involves the systematic application of Value Stream Mapping (VSM), Failure Mode and Effects Analysis (FMEA), and Root Cause Analysis (RCA) to continuously identify process waste, critical failure modes, and their underlying causes. As demonstrated in this study, the combined use of these tools provides a holistic view, linking process bottlenecks directly to equipment unreliability and its root causes. This integrates the framework's objective to identify value-added versus non-value-added steps through VSM and ensure equipment reliability by analysing failure modes and their impact through FMEA and RCA.

✚ **Synergistic Interventions:** This component focuses on deploying targeted Lean and RCM interventions that mutually reinforce each other. Key Lean interventions from the framework include 5S Methodology for workplace organisation, Standard Operating Procedures (SOPs) and Work Instruction for consistent operations, Kaizen (Continuous Improvement) for employee-driven incremental changes, Just-in-Time (JIT) Production to reduce excess inventory, and Kanban Systems to improve workflow by using pull-based systems. These are integrated with RCM-driven interventions such as Autonomous Maintenance

(from Total Productive Maintenance (TPM)), empowering operators with routine preventive tasks, Predictive Maintenance using data-driven insights to forecast failures (e.g., IoT sensors and data analytics for Condition Monitoring and Predictive Analytics), and Reliability-Centered Maintenance (RCM) planning to optimise maintenance tasks based on failure modes and their impact. Bottleneck Analysis and Theory of Constraints (TOC) will focus efforts on optimising the weakest point in the process (e.g., SMED for reducing changeover times at critical bottlenecks).

✚ **Performance Governance:** This element ensures the sustainability of improvements through robust monitoring and feedback mechanisms, directly aligning with the "Define Key Objectives and Metrics" and "Data-Driven Decision Making" aspects of the Lean Reliability framework. It includes tracking comprehensive Key Performance Indicators (KPIs) like OEE, reject rate, NTM waste, Cycle Time, Throughput, DPMO, MTBF, and MTTR, establishing a Computerised Maintenance Management System (CMMS) for data-driven decision-making (supported by Data Collection & Monitoring using IoT devices and MES), and implementing continuous Training and Skill Development programmes for operators and maintenance staff (related to Employee Involvement and Feedback Loops). Regular Performance Reviews and Statistical Process Control (SPC) will monitor process behaviour and ensure it stays within acceptable limits. Additionally, Sustainability Considerations will be integrated to minimise resource consumption and reduce waste for minimal environmental impact.

✚ **Mechanism and Expected Outcomes:** This integrated model operates by creating a feedback loop where reliability insights inform Lean actions, and Lean practices improve maintenance effectiveness. For example, addressing the root cause of "Stop From Tray Filler" lack of preventive cleaning discipline would involve 5S and Autonomous Maintenance initiatives, where operators are trained and empowered to perform routine cleaning and checks, thereby reducing unplanned stops. Similarly, predictive maintenance can forecast sensor miscalibration, preventing "Carding Hopper Empty" failures. This systematic approach is expected to lead to significant improvements: OEE will increase as equipment availability and performance stabilise, reject rates and NTM waste will decrease due to fewer

defects and better material utilisation, and production yield will improve. these outcomes are anticipated over a medium-term timeframe, as they require not only technical interventions but also a cultural shift towards proactive problem-solving and cross-functional collaboration. the model ensures that operational details, while critical, are planned for Chapter 6's recommendations, while this section focuses on the conceptual framework and its evidence-driven components.

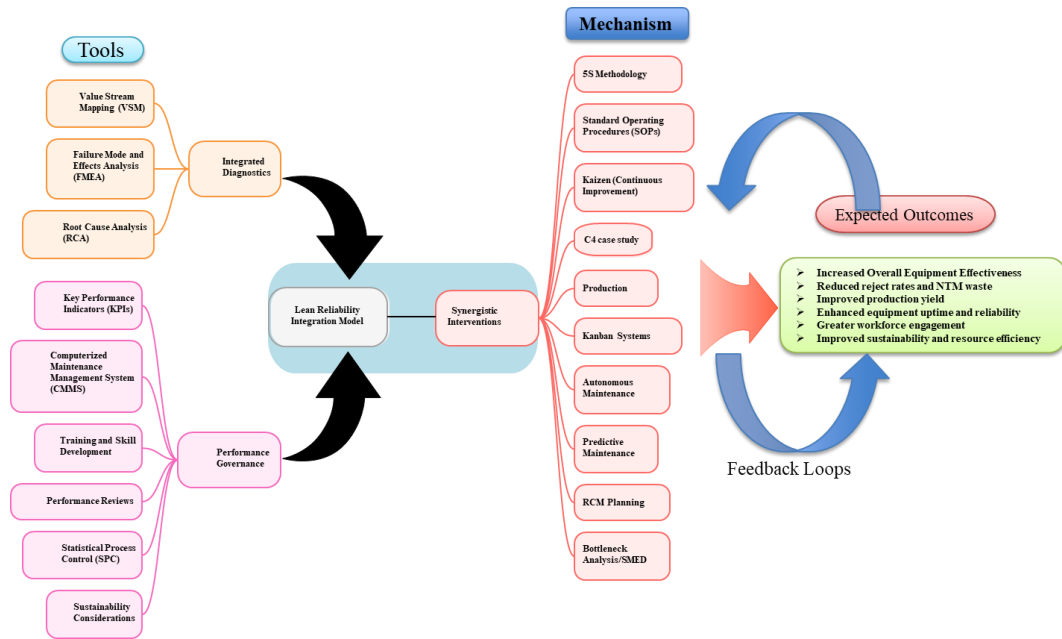


Figure 5.1. Lean-RCM Integration Model for NTE

5.6 Implications of the Findings

The findings from this integrated Lean-RCM study for NTE hold significant implications across operational, managerial, and policy levels, extending beyond the immediate context of the Make-Pack department.

5.6.1 Operational Implications

The chronic operational inefficiencies and high waste rates at NTE necessitate urgent, evidence-backed interventions at the operational level. the persistent deviations in reject rates, NTM waste, and OEE underscore a critical need for streamlined production flow and robust maintenance practices. concretely, the identified bottlenecks at the Maker, Packer, and Cellophaner stages (see Table 4.16 for VSM metrics) demand targeted flow improvement initiatives. For instance, implement SMED (Single-Minute Exchange of Die) techniques at the Maker, Packer, and Cellophaner stages to significantly reduce

changeover times, which is expected to improve machine availability and overall throughput.

In terms of maintenance, the pervasive reliability failures and their root causes (e.g., missed PM, sensor miscalibration, inefficient spare-part management) call for a shift from reactive to proactive strategies. Specific actions should include introducing comprehensive Autonomous Maintenance checklists for Maker machines, particularly addressing the tray-filler stoppages and cleaning discipline issues (root cause of "Stop From Tray Filler"). Furthermore, establishing critical spares Kanban systems for high-impact components, such as those in the Cellophaner (linked to film handling wear and spare-part delays identified in RCA), would mitigate downtime caused by material unavailability. For waste control, the direct empirical link between OEE and waste KPIs (OEE explains 50.8% of reject variability and 78.1% of NTM yield variability) means that improvements in equipment reliability will have a measurable impact on waste reduction. Implementing these targeted maintenance and flow improvements is expected to lead to a direct increase in OEE, which in turn will reduce cigarette reject rates and NTM waste, translating into substantial cost savings and improved resource utilisation. Quantifying these inefficiencies reveals a significant financial burden on NTE. Based on the documented average OEE shortfall of 8.045 percentage points (target 43.90% vs. actual 35.8550%) and an excess NTM waste of 2.3833 percentage points (target 1.00% vs. actual 3.3833%), the estimated average annual operational cost losses for the company are substantial.

Table 5.2 Estimated Average Annual Operational Cost Losses for NTE

KPI	Average Performance	Target	Deviation from Target (%)	Cost per 1% KPI Deviation (USD)	Estimated Annual Cost Loss (USD)
(OEE)	35.86%	43.90%	8.045% (shortfall)	\$17,285	\$139,057.83
(NTM) Waste	3.38%	1.00%	2.3833% (excess)	\$2,645	\$6,303.83
Total Estimated Cost Loss	<i>Note: The "Cost per 1% KPI Deviation" values were obtained through an oral inquiry from the NTE Finance Department.</i>				\$145,361.66

This quantification underscores the significant financial implications of the chronic operational inefficiencies at NTE and highlights the urgency for implementing the proposed integrated Lean-RCM framework. These figures provide a clear economic justification for prioritising and investing in the recommended operational changes.

5.6.2 Managerial and Organizational Implications

Beyond operational fixes, the findings highlight fundamental managerial and organisational challenges. The qualitative data revealed a "predominantly reactive maintenance culture," "insufficient operator involvement," "communication gaps," and Lean initiatives "perceived as management-driven". Addressing these requires a multi-pronged approach:

Firstly, fostering a culture of cross-functional collaboration is paramount. Establishing regular joint production-maintenance meetings and cross-functional improvement teams can bridge communication gaps and ensure that maintenance activities are aligned with production goals, promoting shared ownership of OEE targets.

Secondly, investing in targeted operator training programmes is critical. Training should cover not only Lean tools (e.g., 5S, standardised work) but also fundamental RCM principles, troubleshooting skills, and the importance of adhering to cleaning and PM schedules. Empowering operators with these skills will increase their ownership of machine reliability, thereby reducing unplanned stoppages and improving the consistency of production.

Thirdly, implementing performance incentives tied to OEE, reject rate, and NTM waste metrics can drive behavioral change and align individual and team efforts with strategic objectives. This will shift the focus from merely meeting production targets to achieving sustainable efficiency through reliable operations. The current state, where "low operator ownership of routine checks and limited technical training" persists, underscores the urgency of these managerial interventions.

5.6.3 Industry and Policy-Level Implications

This study's findings also carry broader implications for the tobacco industry and policy-makers, particularly in developing economies like Ethiopia. NTE's high NTM waste rate ($M = 3.38\%$, target 1.00%) not only impacts profitability but also poses significant

environmental concerns, especially given tightening regulations and global expectations for sustainability (Ali et al., 2019). Reducing NTM waste, therefore, directly contributes to NTE's sustainability agenda and helps meet regulatory compliance standards.

From an industry perspective, NTE, as Ethiopia's sole legal tobacco manufacturer, has a unique opportunity to set a benchmark for operational excellence within the national manufacturing sector. By successfully integrating Lean and RCM, NTE can demonstrate a tangible model for optimising waste and enhancing efficiency that can be replicated across other materials-intensive industries facing similar challenges in developing contexts. This could also inform supplier development programmes, encouraging upstream partners to adopt similar efficiency-enhancing practices that contribute to a more sustainable supply chain. At a policy level, the study highlights the importance of fostering an enabling environment for advanced manufacturing practices, potentially through incentives for adopting integrated Lean-RCM frameworks that promote both economic competitiveness and environmental stewardship.

5.7 Academic Contributions

This study makes several significant academic contributions to the fields of Lean manufacturing, Reliability-Centered Maintenance (RCM), and their integration, while also proposing avenues for future research.

Contributions to Lean Literature

This study extends the Lean literature by empirically demonstrating how specific Lean waste categories are intricately linked to quantified reliability failure modes in a high-volume, continuous processing environment, specifically within the tobacco manufacturing sector. Prior Lean studies often conceptualise waste in isolation from the underlying technical failures of equipment. This research provides a measurable bridge between Value Stream Mapping (VSM) insights and maintenance diagnostics, illustrating that observed defects and waiting waste are not merely process inefficiencies but direct symptoms of chronic equipment unreliability. Furthermore, it addresses a notable gap in the literature by focusing on tobacco-specific production waste (e.g., cigarette rejects, NTM waste, leaf spoilage concerns), a sector often underrepresented in Lean studies compared to automotive or electronics industries.

Contributions to RCM Literature

The research contributes to the RCM literature by empirically demonstrating that implementing RCM methods can yield direct and measurable material loss reductions when systematically integrated with Lean flow management. It moves beyond simply showing RCM's impact on equipment uptime (Khasanah et al., 2021) to quantify its effect on tangible waste metrics like reject rates and NTM waste. The study reveals the severe scale of high-RPN failures at NTE, showcasing how a reactive maintenance culture exacerbates these issues, thereby highlighting the immense potential for RCM-driven waste reduction in contexts where Lean practices are weak. This underscores RCM's role not just as an asset management tool, but as a critical enabler for Lean objectives, particularly in materials-intensive industries.

Contributions to Bridging Lean-RCM

The most significant academic contribution of this study is the development and empirical validation of an integrated Lean-RCM framework for optimizing production waste. This research offers novel empirical evidence, particularly through regression analysis, demonstrating a clear and quantifiable link between Overall Equipment Effectiveness (OEE) a core reliability metric and the reduction of Lean waste categories like reject rates (OEE explained 50.8% variability) and NTM yield (OEE explained 78.1% variability). This comprehensive integration, utilising VSM, FMEA, RCA, and statistical analysis, provides a structured methodology that addresses both process inefficiencies and equipment reliability synergistically, offering a more holistic approach than traditionally siloed methodologies. This thesis fills a critical gap in the existing literature (identified in Chapter 2) by providing an empirically validated framework that integrates Lean and RCM principles within the under-researched tobacco manufacturing sector, thereby demonstrating a comprehensive approach to waste optimization and operational efficiency where standalone methodologies have proven insufficient.

5.8 Chapter Summary

Chapter 5 has systematically interpreted the empirical findings of this study, revealing that NTE faces chronic operational underperformance characterised by significantly high cigarette reject rates ($M = 5.02\%$) and NTM waste ($M = 3.38\%$), alongside persistently low OEE ($M = 35.86\%$) and production yield ($M = 89.4\%$). These issues were demonstrably driven by pervasive equipment unreliability, with specific high-RPN failure modes at the Maker, Packer, and Cellophaner stages traced to root causes like missed preventive maintenance, inadequate sensor control, and operator training gaps. The study has established a strong empirical link between OEE and waste reduction, confirming that improving equipment reliability is paramount for achieving Lean objectives, as OEE explained 50.8% of reject rate variability and 78.1% of NTM yield variability. These findings address the research questions by quantifying the waste and efficiency gaps, identifying the primary causes (equipment unreliability and weak maintenance/Lean implementation), and proposing an integrated Lean-RCM framework as a holistic solution. The discussion extends existing literature by providing a measurable bridge between Lean waste categories and reliability failures, particularly in the under-researched tobacco manufacturing sector, and by empirically validating the synergy of integrated approaches.

Chapter Six

Conclusions and Recommendations

6.1 Conclusions

This study set out to optimize production waste and enhance operational efficiency at NTE by integrating Reliability Analysis and Lean Systems, with specific objectives to identify waste causes, assess Lean's impact, analyze integration challenges/benefits, and evaluate RCM's role. Based on the robust empirical evidence gathered and interpreted, the study confidently concludes that these objectives have been successfully met, providing a clear assessment of this study's success against its initial criteria.

The Study conclusively confirmed chronic and statistically significant operational underperformance within NTE's Make-Pack department, establishing the pervasive nature of high reject rates, NTM waste, and low OEE and production yield. This finding directly answers the research questions regarding the magnitude and trends of waste and inefficiency, validating this study's initial problem statement.

The study further identified the specific, high-impact equipment reliability failures and their underlying systemic root causes as the primary drivers of production waste and operational inefficiency at NTE. The rigorous application of FMEA and RCA explicitly linked critical failure modes to issues like neglected preventive maintenance, inadequate sensor control, and inefficient spare-part management. This unequivocally fulfills the objective of identifying the primary causes of production reject and waste, demonstrating that a reactive maintenance culture and deficiencies in planning directly contribute to chronic equipment unreliability.

Moreover, the research established that critical process bottlenecks identified through Value Stream Mapping are directly caused by underlying equipment unreliability. The VSM clearly demonstrated that low uptimes at the Maker, Packer, and Cellophaner stages lead to significant flow disruptions and various forms of Lean waste (e.g., waiting, defects). This confirms that process inefficiencies are fundamentally rooted in

equipment dependability issues, thereby fulfilling the objective of assessing where flow constraints occur and how they relate to waste and reliability. Finally, the study definitively concludes that traditional Lean manufacturing or Reliability-Centered Maintenance interventions, when applied in isolation, are insufficient to holistically address NTE's complex and interdependent operational challenges. The compelling empirical evidence, particularly the strong quantitative link between OEE and waste reduction (explaining 50.8% of reject rate variability and 78.1% of NTM yield variability), validates that a synergistic, integrated Lean-RCM framework is not merely complementary but essential for achieving sustainable optimization of production waste and enhancing operational efficiency within this unique manufacturing context. This research successfully addresses a critical gap by providing an empirically validated framework that integrates these principles for comprehensive waste optimization. In essence, the chronic equipment unreliability at NTE is not merely a technical problem; it fundamentally underpins and exacerbates various forms of Lean waste, highlighting the critical necessity of an integrated approach to achieve meaningful and sustainable operational improvements.

6.2 Recommendations

For NTE's operational teams, it is imperative to formally adopt and implement the proposed integrated Lean-RCM framework, ensuring that process-focused Lean improvements are consistently underpinned by robust equipment reliability strategies. This holistic approach is crucial for moving beyond isolated, ineffective interventions. Specific targeted Reliability-Centered Maintenance (RCM) interventions must be executed: this includes rigorous preventive cleaning and sensor calibration for Maker machines to address "Stop From Tray Filler" and "Carding Hopper Empty" failures; enhanced inter-machine sensor control and recalibration schedules for Packer machines to mitigate "Stop From Cigarette Reserve"; and establishing standardised setup procedures, along with critical spares Kanban systems, for Cellophaner machines to reduce "Stop From Cartoner" and "Film Misalignment" issues. Alongside these, Lean flow optimization techniques like Single-Minute Exchange of Die (SMED) should be implemented at the VSM-identified bottlenecks (Maker, Packer, Cellophaner stages) to reduce changeover times, and Kanban systems introduced to manage work-in-process

efficiently. Furthermore, proactive waste control and quality management measures, including Poka-Yoke (mistake-proofing) at defect-prone points and real-time monitoring systems for waste KPIs and OEE, are essential.

From a strategic managerial and organizational perspective, NTE must foster a culture of cross-functional collaboration by establishing regular joint production–maintenance meetings and dedicated improvement teams to bridge communication gaps, align maintenance activities with production goals, and promote shared ownership of OEE targets. Investing in comprehensive, targeted training programs for operators and maintenance staff, covering core Lean tools, RCM principles, and autonomous maintenance, is critical for enhancing skills and ownership. Implementing performance incentives explicitly tied to OEE, reject rates, and NTM waste, alongside establishing a Computerised Maintenance Management System (CMMS) for robust data collection, analysis, and data-driven decision-making, will drive behavioural change and align efforts with strategic objectives. Ultimately, strengthening leadership commitment is paramount, with management actively championing a cultural shift towards proactive problem-solving and continuous improvement, providing the necessary resources and sustained support. The significant estimated average annual operational cost losses of USD \$145,361.66 due to OEE shortfalls and excess NTM waste provide a strong economic justification for these critical investments.

At the industry and policy level, NTE, as Ethiopia’s sole legal tobacco manufacturer, has a unique opportunity to set a benchmark for operational excellence within the national manufacturing sector. By successfully integrating Lean and RCM, NTE can demonstrate a tangible, replicable model for optimising waste and enhancing efficiency for other materials-intensive industries facing similar challenges in developing contexts. This should extend to promoting sustainable supply chain practices by encouraging upstream partners to adopt similar Lean–RCM practices. Policymakers in Ethiopia should also advocate for strategic incentives (e.g., tax breaks, grants for technology adoption) for manufacturing industries that implement integrated Lean–RCM frameworks, thereby promoting both economic competitiveness by reducing waste and costs, and environmental stewardship by enhancing resource utilisation and reducing the environmental footprint.

6.3 Future Research Areas

While this study provides a solid foundation, several promising directions remain for future investigation. Expanding the scope of research beyond the Make-Pack department would be a logical next step, allowing the proposed Lean-RCM framework to be tested across upstream processes such as tobacco leaf processing and blending, as well as downstream operations like product distribution. This would help validate the scalability and generalizability of the model within NTE and other manufacturing sectors.

Further research could also focus on integrating Industry 4.0 technologies with the Lean-RCM framework. The use of IoT-enabled sensors, predictive maintenance, and real-time data analytics could shift the approach from reactive to proactive, reducing downtime and improving decision-making. Simulation modelling could be applied to evaluate interventions virtually before implementation, optimising maintenance schedules and production flow with minimal risk.

Another important avenue is the deeper investigation of human and organizational factors. Future studies could explore strategies to overcome cultural and behavioural barriers to Lean-RCM adoption, focusing on leadership engagement, operator training, and the role of Autonomous Maintenance (AM) in improving Overall Equipment Effectiveness (OEE) and reducing waste.

Finally, sustainability and supply chain integration present opportunities for further work. Future research could quantify the environmental impact of the integrated framework by measuring reductions in energy use, carbon footprint, and non-recyclable waste. Extending Lean-RCM principles to suppliers and logistics partners could also create a more resilient and sustainable value chain.

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Appendices

Top Downtime Incidents over 30-Month

#	Machine	Failure Mode (Description)	Total Frequency	Total Downtime (hrs)
1	Packer	Stop From Cigarette Reserve	34981	1152.9
2	Maker	Stop From Tray Filler	8849	1006.4
3	Packer	Jam on Exit Channel	11977	419.5
4	Packer	Incomplete Cigarette Pocket	13305	413.1
5	Maker	Rear Rod Break	4806	298.4
6	Maker	Front Rod Break	4694	286.5
7	Packer	No Cigarette In Hopper	9149	285.3
8	Packer	Service Stop	10976	283.9
9	Maker	Carding Hopper Empty	2675	248.8
10	Maker	Paper Break Maker	3241	223.7
11	Packer	Label Jam At Gluer Exit	3232	110.9
12	Cellophaner	Ch Spider; Packet Out Of Position	3618	109.2
13	Packer	Fail; Label Check at Gluer Exist	2364	108.5
14	Packer	5th Wheel Internal Half Ring Jam	2487	106.4
15	Packer	Ineff Check Fail Label Press On Gluer	2182	104.7
16	Maker	Hopper Filter Jam	1563	96.3
17	Packer	Foil Vs Trigger In Efficeny Always Active	1708	95.7
18	Maker	Service Stop Push Button -Maker	1694	94.2
19	Maker	Exit Jam	1585	93.9
20	Maker	Tipper Cork Break Paper Tear Photo Cell -2	1177	91.2
21	Packer	Micro Stoppage	3173	90.7
22	Maker	Tipper Cork Break Paper Tear Photocell-1	1080	82.9
23	Maker	Paper Break Maker- Front	1243	82.4
24	Packer	1stjam On Channel	1349	79.8
25	Packer	Foil Out Of Position	1444	78.4
26	Maker	Paper break maker-rear	1133	73.2
27	Packer	No Cigarettes In Feeder X	1699	71.1
28	Maker	Tipper Cork Break	1011	68.9
29	Maker	Filter Down Feed Jam	1006	68.8
30	Maker	V%VRE SENSOR FAULT CID	743	67.9
31	Packer	Hopper Pusher Guard Open	1441	67.7
32	Cellophaner	Ch Film Missing Or Not Aligned	2014	66.2
33	Cellophaner	Stop From Cartoner	1195	63.5
34	Packer	Foil Drum Torque Regulation	1060	61
35	Maker	Tipper Manual Stop	1317	59.5
36	Cellophaner	Service sTOP Button Pressd	1035	58.7
37	Cellophaner	Stop From Cellephone	1067	58.2
38	Maker	Rolling Block Jam	1096	57.5
39	Packer	Jam 5th Wheel	1456	57.4
40	Maker	Maker Service Stop	1847	56.7
41	Cellophaner	Service Stop	1444	55.9
42	Cellophaner	No Packet In Ch Chain	1828	54.8
43	Packer	Upper Packet Top Heater Not Ready	1013	53.2
44	Cellophaner	Ch Film Folder Flexible Lever	1252	52.7
45	Maker	Feeder Hopper Empty	1080	51.3
46	Maker	Tobacco Down Drop Channel Empty	1018	50.9
47	Cellophaner	Packet Centering Photo Cell Insufficient	1078	50.1
48	Cellophaner	Jam On Ch Entry Channel	1235	48.8
49	Maker	Emergency Stop Button -Cabinet	311	48.7
50	Packer	HHS foil Piston limit stem outside	1125	47.4
51	Packer	No Label On Gluer	1023	46.8
52	Cellophaner	Ch Feed Jam	1013	46.7
53	Packer	Inn Foil Check Fail	1051	46.2
54	Cellophaner	Service Stop; Product Wait	898	44.9
55	Cellophaner	Ch Film Not Aligned	1027	44.3
58	Packer	Label Reserve At Alarm Level	1010	43.9
59	Maker	Tobacco feed stopped	1001	43.7

60	Cellophaner	Ck Absent Over Wrap	1001	43.6
61	Cellophaner	Ck Film Folder Flexible Lever	1010	42.8
62	Cellophaner	Ch Absent Overwrap	999	42.6
63	Packer	foil vs trigger inefficiency always	1000	42.4
64	Maker	Front Guard Open	999	42.3
65	Packer	Sensor Fail Or Bad Packet Pos Existing	987	41.9
66	Packer	4th Wheel Packet Presence Check Fail	985	41.7
67	Packer	No Lower Foil	983	41.4
68	Cellophaner	Right Ch Long Seam Heater Not Ready	975	41.2
69	Cellophaner	Left Ch Long -SEAM Heater Not Ready	974	41
70	Packer	foil reserve at alarm position	971	40.8
71	Packer	Foil Reserve At Alarm Position	970	40.6
72	Cellophaner	Fault LH CH Long Seam Heater Thermostat	968	40.4
73	Cellophaner	Fault Rh Ch Long Seam Heater Thermost	967	40.2
74	Packer	No Foil Reel	965	40
75	Packer	Foil Wrong conditon for change	964	39.8
76	Packer	Aluminium Foil Gluing problem	963	39.6
77	Packer	Too Many Consenctive Rejections 5th Wheel Label Check	960	39.4
78	Packer	Too Many Consenctive Rejections 5th Whell Foil Check	959	39.2
79	Packer	Service Stop Push button -Exit Area	957	39
80	Packer	Service Stop Pushe button Exit Area	956	38.8
81	Cellophaner	Ch Packet Hoper Empty	952	38.4
82	Cellophaner	End Or Breack InCH Tear-Tape	950	38.2
83	Cellophaner	Film Unwinding Jam Ch	949	38
84	Cellophaner	CK MISALIGNED OVER WRAP	947	37.8
85	Cellophaner	CK-Misaligned overwrap	945	37.6
86	Cellophaner	Air pressure check	943	37.4
89	Packer	Jam/Open Door 3rd Wheel	941	37.2
90	Packer	3rd jam on channel	939	37
91	Packer	2nd jam on channel	937	36.8
93	Packer	Label Glue -Flow Blocked	935	36.6
94	Packer	Label Pre-Unwinding Plat Form Open	933	36.4
95	Packer	Label Presence On 3rd Wheel	931	36.2
96	Packer	Too Many Label Posit .Consec Reject	929	36
97	Packer	Too Many Conjective Label Splices	927	35.8
98	Packer	Interminate pressure guard open	925	35.6
99	Packer	Jam Open Door 3rd Wheel	923	35.4
100	Packer	No Label Reel	921	35.2
101	Packer	Insufficent Air Pressure	919	35
102	Packer	Label Glue -Pot Disconnected	917	34.8
103	Packer	No Centering Mark On Label	915	34.6
104	Packer	Label Center Mark -Error Greater Than Max	913	34.4
105	Packer	Outer Foil Check Fail	911	34.2
106	Packer	4th Wheel Jam	909	34
107	Packer	Packet Presence in 5th wheel undesired	907	33.8
108	Packer	Label Positon Wrong On Gluer	905	33.6
109	Packer	Engaged Hand Wheel	903	33.4
110	Packer	Mechanic	901	33.2
111	Packer	HHS Glue level Insufficient	899	33
112	Packer	Adjustment Electrical	897	32.8
113	Packer	Repair Electrical	895	32.6
114	Packer	Repair Mechanical	893	32.4
115	Packer	Cleaning Unplanned	891	32.2
116	Packer	Stop From Cabinet	889	32
117	Packer	Long Stop Cycle Completed	887	31.8
118	Packer	Bundle Jam in Pocket	885	31.6
120	Packer	foil unwinding place form open	883	31.4
121	Packer	Lower Alu Foil Check Failure	881	31.2
122	Packer	Jam Detected From Blank Suction	879	31
123	Packer	Wrap Check on 2nd-3rd Wheel Breakdown	877	30.8
		Total	228275	10038.4

30-Month Key Performance Indicators (KPIs)

Month Year	Reject Rate Percent	OEE Percent	Production Yield Percent	Production Volume Units	NTM Waste (%)Waste	NTM Yield (%)
Jan-2022	4.91	36.38	85.45%	249,100,000	3.07	96.93
Feb-2022	5.39	35.11	86.97%	253,700,000	3.46	96.54
Mar-2022	5.8	33.24	85.42%	249,000,000	3.86	96.14
Apr-2022	7.48	28.84	81.73%	238,160,000	5.38	94.62
May-2022	8.49	26.09	81.29%	281,910,000	6.32	93.68
Jun-2022	7.86	29.96	81.82%	265,120,000	5.74	94.26
Jul-2022	7.32	31.54	82.67%	338,140,000	5.25	94.75
Aug-2022	4	25.88	81.64%	249,830,000	5.99	94.01
Sep-2022	8.88	25.76	85.36%	218,620,000	6.67	93.33
Oct-2022	6.44	29.67	85.14%	293,400,000	4.41	95.59
Nov-2022	5.95	28.22	91.34%	304,310,000	4	96
Dec-2022	4.55	30.37	88.76%	313,650,000	2.61	97.39
Jan-2023	5.87	31.42	91.85%	283,230,000	3.21	96.79
Feb-2023	4.43	38.86	90.58%	290,030,000	2.73	97.27
Mar-2023	4.5	34.78	89.61%	425,760,000	2.75	97.25
Apr-2023	4.94	35.87	89.58%	390,840,000	2.84	97.1
May-2023	3.56	39.99	92.49%	365,330,000	3.21	97.66
Jun-2023	4	38.46	90.98%	371,410,000	3.05	97.49
Jul-2023	5	39.79	91.99%	266,230,000	3.01	97.55
Aug-2023	3.55	39.86	93.66%	386,080,000	3.53	97.67
Sep-2023	3.22	40.41	93.81%	300,180,000	3.8	97.8
Oct-2023	4	47.36	93.74%	428,460,000	1.88	98.12
Nov-2023	6	43.41	94.28%	321,260,000	1.89	98.11
Dec-2023	5	41.42	92.28%	366,900,000	1.12	98.88
Jan-2024	2.84	42.66	92.97%	248,670,000	1.71	98.29
Feb-2024	3.21	42.99	93.69%	378,400,000	1.95	98.05
Mar-2024	3.05	38.76	92.92%	259,950,000	1.85	98.15
Apr-2024	3.01	42.72	94.03%	426,020,000	1.82	98.18
May-2024	3.53	37.47	92.39%	280,910,000	2.1	97.9
Jun-2024	3.8	38.36	93.53%	311,510,000	2.29	97.71