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Optimizing Overall Equipment Effectiveness (OEE) in the Textile Industry Bangladesh (Esquire Knit Composite Limited): A Mixed-Methods Approach to Manufacturing Efficiency

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ABSTRACT:

This study investigates the optimization of Overall Equipment Effectiveness (OEE) within the textile industry of Bangladesh, specifically focusing on Esquire Knit Composite Limited, to address the sector's need for enhanced manufacturing efficiency and sustainability in response to current industry demands. The study merged mixed methods, combining an integrated analysis of OEE based on quantitative assessments with qualitative information. Data was collected using a historical review of performance data, in-depth interviews and specific case studies to determine the primary influencers on OEE. The research identifies critical OEE contributors and evaluates the importance of introducing lean principles and sustainable approaches for better OEE. The research reveals significant OEE deficiencies within the studied context, highlighting substantial opportunities for improvement in manufacturing efficiency at Esquire Knit Composite Limited. The analysis of OEE data and qualitative insights provide a basis for recommending targeted optimization approaches. The investigation extends the existing, rather scarce empirical research on the optimization of OEE in the Bangladeshi textile sector. By integrating quantitative OEE analysis and qualitative lean manufacturing and sustainability insights, the study gives a complete view on how to boost manufacturing efficiency in this critical sector. These findings act as an instructive resource for efforts to improve performance and sustainability of the Bangladeshi textile market.

KEYWORDS: Overall Equipment Effectiveness (OEE), Textile Manufacturing, Lean Manufacturing, Preventive Maintenance, One-Piece Flow, Autonomous Maintenance, Mixed-Methods Research, Industrial Efficiency, Sustainability.

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Abbreviations

AI - Artificial Intelligence
BGMEA - Bangladesh Garment Manufacturers and Exporters Association
CE - Circular Economy
CMMS – Computerized Maintenance Management System
CPM - Critical Path Method
CPM-Cost Per Minute
GSP - Generalized System of Preferences
JIT - Just-in-Time
IoT- Internet of Things
LCA - Life cycle assessment
MFA - Multi-Fiber Arrangement
MTBF - Mean Time Between Failures
MTTR - Mean Time to Repair
OEE - Overall Equipment Effectiveness
OEKO-TEX- International Association for Textile Sustainability Certification
PTS - Primary Textile Sector
RFT - Right First Time
RMG - Ready-Made Garment
SMED - Single Minute Exchange of Die
SMEP - Single Minute Exchange of Process
SPC - Statistical Process Control
SVSM - Sustainable Value Stream Mapping
TBL - Triple Bottom Line
TPM - Total Productive Maintenance
TPS - Toyota Production System
VSM - Value Stream Mapping

1 Introduction

1.1 Background of the Research

The garment and textile industry in Bangladesh is vital since it helps the country's economy by producing a major part of its GDP and exports and creating many job opportunities. Between the 1980s and the present day, Bangladesh has grown to become one of the biggest clothing export countries in the world and now stands as second to China (World Trade Organization, 2021). Successful operations in the industry are due to reasonable labor prices, helpful trading laws, and having an established system for making large amounts of products inexpensively.

The export oriented ready-made garment (RMG) factories started shifting the textile industry of Bangladesh towards prominence during the late 1970s and the early 1980s. Local entrepreneurs took control of this industry through favorable market access provided by the Multi-Fiber Arrangement (MFA) (Rahman, et al., 2019). Bangladesh continued to improve its global textile market position after the MFA ended by using its qualified labor force along with affordable labor costs while investing in manufacturing site development. Total RMG exports continue to grow at a fast pace because they make up more than 80% of all $45.7 billion garment exports which were recorded in 2022 according to Bangladesh Garment Manufacturers and Exporters Association (BGMEA) (2022). The largest markets for Bangladeshi apparel exist between the European Union and the United States because of their trade preferences under the Generalized System of Preferences (GSP) program.

The Bangladesh textile sector operates in three basic segments where Primary Textile Sector (PTS) consists of spinning weaving and dyeing operations that supply materials to the RMG industry. A steady textiles and yarn supply depends heavily on the primary textile sector which protects Bangladesh from dependency on imported materials (Bangladesh Textile Mills Association, 2021). The RMG Sector stands as the industry's leading segment since it creates completed clothing products for worldwide export. The manufacturing facilities of both woven and knit products make up this sector (BGMEA, 2022). The traditional handloom industries alongside cottage industries generate textile production both for home consumption and to safeguard the fabric traditions of hand-made products (Ahmed et al., 2020).

The textile and garment sector operates as the biggest job creator in Bangladesh with more than 4.4 million workers yet 65% of the workforce comprises female employees (BGMEA, 2022). The disproportionate number of female workers in the sector has brought social evolution by giving women economic power which enables their independence from traditional societal rules. Several pressing topics regarding labor rights and workplace safety together with fair wages continue as major concerns within the Bangladeshi textile industry since the Rana Plaza collapse in 2013 (Khan & Wichterich, 2015).

OEE stands as a lean manufacturing technique for measuring system effectiveness by assessing equipment functionality and product quality and operational speed (Hossen, 2016). Haddad, Shaheen and Nemeth (2021) showed OEE serves as an outstanding indicator which measures sustainability improvements within organizational production systems from their initial condition (Haddad et al., 2021). Production industries across the world work daily to improve their efficiency and productivity while also seeking sustainable practices to fulfill global market requirements. The measurement of equipment effectiveness allows organizations to evaluate their manufacturing resource and equipment utilization during production activities. Plants grow best through this method that serves as a top strategy for their development (Shar et al., 2021). Overall Equipment Effectiveness (OEE) emerges as one of several performance measurement tools because it offers a comprehensive evaluation system for operational performance. OEE entered the manufacturing world as the central element of TPM during the 1980s before establishing itself as an essential principle of lean manufacturing (Nakajima, 1988). OEE combines availability with performance and quality to provide businesses with a complete measurement of industrial efficiency.

Total global manufacturing output heavily relies on the textile industry because it generates millions of jobs across the world and maintains itself as a foundational element for developing countries. Industrial producers of textiles face challenges to drive innovation while preserving both their operational efficiency and sustainable efforts because market customers demand new products. Bangladesh experiences extreme tension between these two priorities since their textile and clothing exports drive approximately 80 percent of all export revenue (World Bank, 2022). OEE optimization stands as both an operational necessity and an economic obligation in the textile industry sector.

1.2 Problem Statement and Reserach Questions

The main obstacle in the textile sector of Bangladesh arises from machines being idle due to both unexpected maintenance needs and poor operational scheduling. Machine downtime stands as the primary cause of production delays in Bangladesh's garment factories where it amounts to about 30% according to Chowdhury, Ahmed, and Hossain (2020). The manufacturing problems reduce operational productivity while increasing operational expenses which create barriers to market competitiveness for companies.

The reliance on old machinery creates a major obstacle for businesses to achieve their maximum OEE scores. Several textile manufacturers in Bangladesh continue to use production machinery that does not feature either machine learning automation or predictive maintenance systems. Bangladesh textile manufacturers operate with outdated legacy systems that limit their ability to align industry performance with future potential development (Salman et al., 2024).

Weak data collection and analysis systems operate as a major obstacle to the problem. The computation of OEE depends on obtaining precise and fast data collection from availability, performance, and quality metrics (IBM, 2023). The collection and analysis of data remains impeded by textile companies who do not have sufficient technology systems for handling these processes effectively. The insufficient data collection systems prevent organizations from discovering operational problems while developing specific improvement methods.

Organizations experience great challenges because of their resistance to change. Company barriers to change along with insufficient understanding of OEE improvement benefits create resistance to adopting different approaches or technical solutions. The cultural environment needs to transform itself first to prioritize ongoing improvement practices along with innovative thinking.

This study seeks to answer the following key research questions:
1.How can Overall Equipment Effectiveness (OEE) be optimized in textile industry manufacturing operations to enhance efficiency and support sustainability goals in the textile and garment sectors?

2. What are the key factors influencing Overall Equipment Effectiveness (OEE) in textile manufacturing operations, and how can these be measured and analyzed to identify areas for improvement?

3.What mixed-methods approach strategies and tools can be applied to optimize OEE while aligning sustainability objectives in the textile and garment sectors?

1.3 Objective of the Research

The objective of the study is to

1.To identify and analyze the key factors influencing Overall Equipment Effectiveness (OEE) in textile manufacturing operations.

2.To explore and evaluate the role of lean manufacturing practices and sustainability initiatives in optimizing OEE within the textile and garment sectors.

3.To propose a mixed-methods approach for optimizing OEE that aligns with sustainability goals, including the application of tools and strategies from both qualitative and quantitative research.

1.4 Scope of the Study

Many textile producer from Bangladesh experience rising competition in the global market because emerging nations such as Vietnam and Ethiopia now match Bangladesh's production expenses (Textile Today, 2023 ; Posh Garments, 2023 ; The Textile Magazine, 2023). The textile industry requires product range diversification to implement green technology solutions and training its entire production value network for sustaining competitiveness. The textile businesses in Bangladesh can boost their operational efficiency through implementation of IoT and AI from the Industry 4.0 technologies (Chowdhury et al., 2020). The industry needs to tackle sustainability problems concerning environmental effects and resource management together with social compliance to maintain industry competitiveness over the long term.

The research concentrates on Bangladesh territory while conducting an extensive study at Esquire Knit Composite Limited. This study fails to conduct comparative evaluations between the textile industries in Bangladesh or any textile industries worldwide. The research analyzes the effect of operational methods on organizational efficiency within one specific organization through detailed OEE evaluations. The investigation explores amalgamations of IoT technologies with predictive analytics techniques that enhance OEE optimization practices, but the study does not include analysis of comprehensive Industry 4.0 implementations throughout the textile industry. This investigation includes sustainability elements but avoids performing a complete environmental impact evaluation. The investigation excludes all aspects beyond manufacturing operations at Esquire Knit Composite Limited since it only concentrates on study activities within the plant. The study establishes precise borders to maintain the targeted and detailed analysis of OEE improvement practices in the chosen production facilities thus preventing the generation of generalized information outside the research boundaries.

1.5 Thesis Structure

This thesis is divided into six essential chapters which examine crucial research elements starting from problem recognition up to analysis and suggested solutions.

Chapter 1: Introduction

The first section introduces the research by providing an overview of the research scope and objectives. The background of this study along with the problem identification and research objectives follows the presentation of research questions. The first section demonstrates the importance of the research by describing its significance alongside its boundaries while establishing why the topic matters to the domain.

Chapter 2: Literature Review

A complete review of OEE optimization theories together with assessments of lean manufacturing concepts and industrial analytics techniques and sustainability practices within the textile sector gets discussed in this section. A thorough evaluation of conceptual and empirical work in the field enables identification of missing knowledge which supports why the current study is necessary. The theoretical framework includes discussions of TPM, Six Sigma as well as Industry 4.0 to support optimization of OEE.

Chapter 3: Research Method

The research implementation and methodology plan are explained in this section. The study adopts a mixed-methods method which integrates qualitative and quantitative research investigation approaches. The data gathering techniques described in this section consist of surveys and interviews together with case studies and factory observation methods. The study methodology indicates selection methods for samples along with analysis strategies alongside ethical procedures that maintain the study’s validity and reliability.

Chapter 4: Results and Analysis

The results and analysis chapter presents the findings from the collected data, offering both quantitative and qualitative interpretations. Quantitative analysis is used to evaluate OEE performance metrics, identifying inefficiencies, and comparing results against industry benchmarks. Qualitative insights from interviews and case studies provide contextual understanding of OEE implementation challenges and best practices. The findings are discussed in relation to the research questions and existing literature.

Chapter 5: Findings and Discussions

The chapter brings together significant results derived from quantitative and qualitative data methods. The incorporation of mixed-methods analysis allowed researchers to obtain complete knowledge about Overall Equipment Effectiveness (OEE) during textile manufacturing processes. The analysis examines outcomes through the research objectives to find major OEE influences which include equipment availability and repair protocols and workflow systems and worker competencies. The paper explores the real-world implications for preventive maintenance and lean manufacturing while conducting its assessment. The findings also examine study constraints, and they establish a connection between operational performance gains and sustainable objectives.

Chapter 6: Conclusions and Recommendations

The research investigation reaches its conclusion by presenting important study results for textile market applications. The study presents practical advice to enhance OEE measurements through sustainable implementation alongside methods to address the difficulties encountered. The research study points out its limitations which suggests future investigation paths for manufacturing optimization methods within the production sector.

2 Literature Review

2.1 OEE Definition and Overview

OEE is defined as a key performance indicator that measures how efficiently a manufacturing process is operating using availability, Performance, and quality. It calculates the percentage of scheduled production time that is truly productive; identical to provides a way to determine where gain potential exists in your equipment utilization and operational efficiency (Nakajima, 1988).

OEE serves as a standard performance assessment tool which determines equipment manufacturing efficiency during operations. Operators calculate OEE through evaluation of availability alongside measurement of performance together with assessment of quality as a ratio between defect free products and complete output (Lean Production, 2023). The achievement of 100% OEE score indicates perfect manufacturing efficiency due to equipment operation throughout scheduled time at maximum speed and free from defects (IBM, 2023).

The textile industry needs optimized OEE measurements to achieve maximum efficiency and productivity because fast production cycles combined with high output numbers directly determine successful competition in this field. The improvement of OEE increases more machine availability while lowering operational expenses and strengthening product quality to achieve better resource efficiency and sustainability. Higher OEE scores generate better financial results by cutting down nonproductive periods as well as material loss. The implementation of Industry 4.0 technologies specifically IoT and AI-driven predictive analytics systems allows textile manufacturers to conduct predictive equipment performance monitoring and failure prediction and real-time optimization which results in improved OEE outcomes (Chowdhury et al., 2020).

The calculation of OEE depends on three major factors which consist of machine downtimes and quality problems together with performance limitations. Manufacturing downtime which results from unplanned equipment failures combined with maintenance holdups and operator errors decreases operational availability and reduces complete production effectiveness according to LinkedIn (2023). The quality component of OEE decreases when manufacturing defects, rework tasks and inconsistent raw materials appear as quality issues according to PMC (2023). Running machines at suboptimal speeds coupled with routine operational disruptions both decrease productivity levels because they affect the performance component of OEE (Symestic, 2023). The optimization of OEE requires that manufacturers address quality control and production monitoring challenges through preventive maintenance and advanced quality control systems and real-time production monitoring (Nakajima, 1988). Manufacturers achieve better equipment reliability by adopting predictive maintenance practices which prevent surprises and uphold superior quality assurance methods that stop product flaws and reprocessing events. Process automation in combination with data-based decisions improves productivity rates and eliminates production areas that need improvement (Lee et al., 2013).

2.2 Lean Manufacturing and OEE Optimization

Lean manufacturing is defined as a method that helps to minimize waste while maximizing productivity (Womack & Jones, 1996). According to Womack & Jones (1996) lean manufacturing can be applied as a process enhancement system which seeks to remove unnecessary expenses while optimizing manufacturing workflows as it increases production speed through quality centric production practices .The methodology follows five essential principles including value identification together with value stream mapping and flow creation and pull based production with the additional element of Kaizen continuous improvement (Liker, 2004). The production process remains streamlined because these principles help decrease operational inefficiencies while maximizing machine effectiveness. The improvement of Overall Equipment Effectiveness (OEE) is supported by lean manufacturing through implementation of the Total Productive Maintenance (TPM) tool for breakdown reduction as well as Just-in-Time (JIT) for inventory control alongside 5S for workplace organization and Value Stream Mapping (VSM) for process optimization (Bhasin & Burcher, 2006). Thus, it is reasonable to say OEE optimization and lean manufacturing goes hands by hand. Here, OEE optimization refers to the process of systematically improving the availability, performance, and quality components of Overall Equipment Effectiveness to maximize productive manufacturing time.

Lean manufacturing principles within textile operations boost operational equipment readiness and enhance manufacturing pace and manufacturing product excellence. TPM operates across textile weaving and knitting facilities to decrease machine outage time simultaneously strengthening equipment operation stability and JIT contributes to streamlined material flow together with minimized inventory levels throughout garment production (Tortorella et al., 2020). The measurement of OEE receives better accuracy through Industry 4.0 technologies which include IoT predictive maintenance together with AI-based quality control systems (Bokrantz et al., 2017). Manufacturers implementing adapted lean principles for textile production can reach cost savings combined with better energy performance and sustained market competitiveness in the global marketplace.

Lean manufacturing relies on Overall Equipment Effectiveness (OEE) as its primary performance index to measure availability alongside performance and quality standards (Nakajima, 1988). Research on OEE optimization takes place frequently in manufacturing environments (Muchiri et al., 2008). The deployment of lean manufacturing concepts JIT and TPM boosts OEE performance by working to minimize waste and maximize equipment operational efficiency according to (Sharma et al., 2018). Accomplished organizations report enhanced results in reduction of downtime along with improved machine reliability and prevention of defects.

Research indicates that uniting Lean and OEE methodologies produces greater productivity together with improved operational efficiency (Bhasin & Burcher, 2006). The implementation of Value Stream Mapping (VSM), 5S and Kaizen along with other Lean tools helps manufacturers reduce waste and maximize machine operational efficiency

(Womack & Jones, 1996). The Toyota Production System (TPS) serves as a perfect illustration of how lean implementation generates higher Overall Equipment Effectiveness values across manufacturing processes (Liker, 2004).

Industry 4.0 technologies particularly predictive maintenance together with artificial intelligence (AI), and machine learning enable the modern advancement of OEE optimization. Manufacturers use these technological systems to analyze data in real time and predict equipment failures while planning effective production schedules (Bokrantz, et al., 2017). Intensive investments towards digitization and smart manufacturing implementation lead organizations to achieve higher equipment performance levels at lower operational expense rates.

Research cases show that companies following lean-based OEE methods gain better employee involvement as well as enhanced competency development which builds continuous improvement cultures (Tortorella et al., 2020). Top capacity management success relies on employee involvement, which maintains available system time and establishes uniform operational practices for lasting OEE results. Organizations attaining better operational resilience and long-term competitive advantage reach it by aligning OEE initiatives with lean manufacturing principles.

2.3 OEE Measurement and Frameworks

The manufacturing industry relies on Overall Equipment Effectiveness (OEE) as its primary performance metric to measure production equipment efficiency through the evaluation of Availability, Performance and Quality according to Nakajima (1988). According to Muchiri and Pintelon (2008) a manufacturing machine reaches maximum efficiency if its performance score reaches 100% (Nakajima, 1988). Industry uses four main frameworks for OEE measurement, among which are Nakajima’s traditional model, the Six Big Losses approach, Total Productive Maintenance (TPM), and Industry 4.0-driven smart OEE measurement (Sharma et al., 2018). The textile industry utilizes OEE measurements to keep track of productivity in spinning, dyeing and garment production because these functions experience performance declines from machine stoppages and speed instability together with defective fabric output. The availability calculation for a knitting unit amount to 90% when production time spans 10 hours yet downtime lasts one hour during this period. The performance score of the machine becomes 90% when its operating speed reaches 90% of maximum. OEE computes to 76.95 when quality reaches 95% while defects amount to 5% of total fabric production. The calculations enable manufacturers to detect operational inefficiencies which they can address using TPM and JIT and VSM and predictive maintenance systems to boost OEE (Silver & Burcher, 2006). Industry 4.0 technologies, including real-time IoT monitoring, AI-driven predictive analytics, and automated alerts, have improved the accuracy of OEE measurement while facilitating ongoing process improvements (Bokrantz et al., 2017). Textile manufacturing relies on MTBF as well as MTTR alongside RFT and energy efficiency tracking metrics to improve analysis of equipment dependability and quality control and operational energy use (Tortorella et al., 2020). The combination of developed OEE frameworks together with digital manufacturing solutions enables textile organizations to reach better production efficiency and lower expenditures while maintaining successful global market positions.

The measurement methods for OEE differ according to industry type (Muchiri et al., 2008). The integration of Six Sigma and TPM methodology brings enhanced capabilities in OEE tracking and benchmarking according to Jeong and Phillips (2001). Industry 4.0 tools particularly predictive maintenance and IoT-enabled real-time monitoring to have improved OEE frameworks according to (Bokrantz et al., 2017).

OEE measurement accuracy depends on a specific framework which includes availability of machines and efficiency of performance and quality of output. The standard framework for OEE evaluation involves collecting production metrics for efficiency computations through established calculations (Nakajima, 1988). The traditional methods encounter two problems which include unreliable data recording and limited integration with digital contemporary devices (Muchiri & Pintelon, 2008).

The shortcomings of the OEE evaluation method inspired researchers to create hybrid frameworks which bring together monitoring systems with SPC and AI technology from Jeong and Phillips (2001). Through IoT enabled devices working with cloud computing platforms manufacturers can achieve precise data while detecting operational inefficiencies as they happen and taking specific remedial steps (Lee et al., 2014).

Companies employ benchmarking to measure OEE because it helps them analyze industry standards which reveal areas for improvement (Hansen, 2002). Six Sigma approaches employed by organizations lead to improved OEE outcomes by performing process improvement alongside defect prevention (George, 2002). Research has validated the integration of OEE metrics into enterprise resource planning systems because it simplifies data management processes and decision-making (Bokrantz et al., 2017).

Standardized OEE measurement adoption continues to face challenges while organizations from different manufacturing sectors attempt to implement this system. The outcome of OEE evaluation depends on machine system intricacy and differing work routines and employee conduct patterns which demand tailor-made measurement systems for industrial requirements (Dal et al., 2000). Studies should develop OEE systems for modern manufacturing technologies while preserving environmental sustainability measures.

2.4 Mix Method Optimization and Industrial Analytics

Modern manufacturing optimization involves building efficiency along with waste reduction and productivity enhancement through data-based strategic approaches according to Tortorella et al. (2020). Industrial analytics bases its operations on real-time production data analysis through big data and artificial intelligence (AI) and predictive analytics to find inefficiencies and promote better decisions (Bokrantz et al., 2017). The combination of these approaches optimizes equipment performance through OEE since it reduces downtime and supports better operation and product quality.

Industrial analytics optimizes the production throughput of OEE through an analysis of machinery efficiency and failure prediction followed by production schedule optimization. IoT sensors installed in textile and garment manufacturing facilities measure loom efficiency alongside machine speed and defect counts allowing them to conduct predictions that identify maintenance needs before equipment breakdowns can occur (Ribeiro et al., 2021). The quality inspection system powered by AI detects fabric stitching errors and defects that lead to decreased material waste along with minimal rework requirements (Lee et al., 2014). The simulation function of digital twins allows testing of new production protocols before actual deployment to confirm peak operational effectiveness. Through these technologies garment manufacturers can obtain improved OEE results in combination with decreased manufacturing expenses and environmentally friendly production methods.

A combination of quantitative and qualitative research methods delivers an extensive mechanism for OEE evaluation (Tashakkori & Teddlie, 2010). The combination of biological and numerical approaches has enabled manufacturing analytics operators to strengthen their OEE predictions through machine learning joint with statistical modeling (Tortorella et al., 2020). The implementation of digital twin technology together with AI diagnostics allows OEE optimization systems to benefit from improved decision-making processes (Ribeiro et al., 2021).

The integrated research approach enables scientists to discover OEE performance limits by exploring operational issues and staff actions and technological boundaries (Tashakkori & Teddlie, 2010). Data-driven decision models assist manufacturers to discover real-time causes of system breakdowns and product defects and production speed drops thereby enabling specialized improvement plans (Tortorella et al., 2020).

The optimization of OEE depends heavily on industrial analytics capabilities because it allows organizations to perform predictive maintenance and identify anomalies and create performance forecasts. The application of digital twins as virtual manufacturing system duplicates lets organizations run live simulations and optimize processes preceding physical implementation according to Ribeiro et al. (2021). Through these technologies machines become more dependable while maintenance expenses decrease alongside decreased production stoppages.

Modern OEE optimization leverages artificial intelligence and big data analytics to enhance pattern recognition and enable predictive insights. Machine learning algorithms use historical data to recognize patterns and discover relationships between variables as well as potential system breakdowns so maintenance operations can be done ahead of time (Lee et al., 2014). The implementation of industrial analytics with smart factory systems creates automated data collection systems and continuous improvement systems which conform to Industry 4.0 principles (Bokrantz et al., 2017).

The effectiveness of utilizing mixed-method optimization depends strongly on three factors which include well managed data quality together with strong research methodology and appropriate organizational preparedness for digital change initiatives. The general implementation of industrial analytics faces barriers from data silos alongside staff opposition to changes and a shortage of analytics experts (Tashakkori & Teddlie, 2010). Future investigations should create adaptive systems which merge real-time data display tools with artificial intelligence decision systems and disciplinary team collaboration to boost Overall Equipment Effectiveness (OEE) performance.

2.5 Sustainability in Manufacturing

Industrial production systems that combine responsible environmental practices with economic sustainability known as sustainability in manufacturing (Seuring & Müller, 2008). The goal of sustainable manufacturing stands to preserve industrial profitability by holding responsible care for the environment and society which enables industry to fulfill current needs without cutting off future resource availability. The textile industry deals with sustainability problems due to its excessive resource usage as well as carbon footprints and waste production according to Choudhury (2017). A solution to these challenges requires businesses to use renewable resources together with waste reduction and energy-efficient process execution (Ghobakhloo, 2020).

Decreasing energy waste becomes vital through OEE optimization because this process makes equipment more efficient and minimizes resource consumption. When manufacturers apply OEE improvements to their operations they create sustainability outcomes because they control equipment breakdowns while extending equipment life and decreasing material waste (Allwood et al., 2012). The optimization of machines for availability and performance and quality yields halved energy consumption and shortened downtime while decreasing excess materials usage thus meeting United Nations Sustainable Development Goals 9 (Industry) and 12 (Production) (United Nations 2015).

The direct impacts of energy conservation measures in the textile industry because of undertaking lean production strategies like the Total Productive Maintenance (TPM) and Just-in-Time (JIT) (Kumar et al., 2021). The guarantee of a safe working environment with developed staff and healthy personnel still is important for the preservation of production by means of social techniques. Better OEE motivates the organizations to create safe working space with operational consistency as the failures of machines become less and bottlenecks become fewer, and this leads the employees to be satisfied as per Sharma et al. (2021).

Industry 4.0 technology such as IoT and AI, and predictive maintenance systems make the manufacturing processes more sustainable (Jayal et al., 2010). IoT sensors enable manufacturers to monitor the real-time performance of their equipment for detection of deficiencies of operation and optimization of energy use as well as avoid unforeseen shutdown of equipment. Companies use AI techniques in conjunction with machine learning approaches to be able to detect pieces of equipment problems even before they occur, hence, they can reduce operational delays and manufacturing waste, as well as reduce the environmental impact (Tao et al., 2018).

There are three important components of the path to sustainable manufacturing namely cleaner production techniques and circular economy models and supply chain sustainability initiatives (Garetti & Taisch, 2012). Hindrances of implementing sustainable manufacturing include the cost of initial investments and employees' lack of willingness to transform and lack of sufficient understanding about sustainability (Jabbour, et al., 2020). The implementation of green technology entails government and international organizations' inputs, which can only generate environmental legislation and financing initiatives to support green technology options. Also, it is observed that companies that become lean and green with Industry 4.0 technologies create efficient and sustainable operations, which serve as a source of resilience throughout the manufacturing industry (Kamble et al, 2018).

2.6 Environmental Sustainability and Resource Efficiency

The textile industry engages in sustainable manufacturing through the initiatives to reduce environmental outputs and yet maximize operational accomplishments and resource usage. Sustainable manufacturing in the context of the textile industry comprises sustainable ways of manufacturing with the use of resource efficient producing processes, waste re-duction programs, sustainable material obtaining processes, and smart manufacturing solutions' implementation. Environmental objectives receive assistance as such practices are incorporated, thus, Overall Equipment Effectiveness (OEE) improvements are achieved through the machine availability and performance and quality levels enhancement (Jayal et al., 2010).

Textile sustainability includes energy efficiency because textile production demands high energy consumption through spinning processing and weaving and dyeing and finishing operations. A combination of high efficiency motors together with renewable energy resources and automated energy management systems cuts down energy loss without impacting production efficiency levels. Manufacturers can optimize production processes through real-time energy monitoring enabled by IoT systems since this approach brings down unexpected breakdowns and enhances machine operation (Tao et al., 2018).

Water management for textile production is essential, as the dyeing, and finishing operations require vast amounts of water to function and produce contaminated wastewater flows. In targeted systems can be used by manufacturers to reduce water wastage and pollution through creating closed-loop dyeing processes and various water recycling and filtration-based processes. The innovations maximize the productivity of machines while still ensuring operational flow to enhance the OEE performance through efficient utilization of water (Sharma et al., 2021).

An approach that uses the circular economy allows the textile manufactures to save waste as well as reuse potential materials and recycled products from sewing scraps and damaged materials. The application of remanufacturing methods incorporating the textile fiber recycling operation allows companies to reduce material costs and improve operational efficiency hence achieving better OEE outcomes due to lower defect rates and a reduced time over which materials get reworked (Jabbour et al., 2015).

Total Productive Maintenance (TPM) and Just-in-Time (JIT) under the lean manufacturing precepts sustain effectiveness of sustainability efforts by ensuring that there are no wastes and there is efficient machine working. These methodologies enhance the makeup time of the machine due to less unplanned downtimes and hence improved performance based on the constant speed conditions, as well as achieving the reduction of the defects to provide better OEE results (Kumar et al., 2021).

With the fact that the textile manufacturers are looking for sustainability alignment with OEE optimization they implement state-of-the-art industry 4.0 practices including Artificial Intelligence (AI), IoT sensors and intelligent automation. Deployment of such technologies enables businesses to monitor production processes in real-time and perform maintenance forecasts for scheduling and perform automated system enhancements for the best machine performance. AI-enhanced defect detection system, once adopted by manufacturers, however, lead to improved product quality whilst reducing material losses and time to a minimum, saving the environment and enhancing OEE performance (Ghobakhloo, 2020).

OEE optimization in the case of weaving industry is also provided with an extra boost via the implementation of sustainability certifications, as well as the obligations in relation to environmental regulations compliance. Resource efficiency in the fabrication of textiles is based on standards such as, the ISO 14001 Environmental Management Systems combined with the OEKO-TEX® Sustainable Textile Production. Adoption of the standards brings in two-fold rewards in reinforcing the company sustainability performance and operational efficiency and cost reduction that contribute to OEE improvement (United Nations, 2015).

Textile manufacturers that combine sustainable input with a better operation effectiveness effort will achieve sustainable profitability and the reduction of environmental impact alongside the increase in the operational productivity. Sustainable resource management in conjunction with smart technology in conjunction with lean manufacturing methods ensures that the textile manufacturing industry becomes stronger and more efficient while at this the industry is environmentally friendly.

Environmental sustainability and resource efficiency are simultaneously considered to be two major components of modern manufacturing that contribute to the environmental reduction and enhancements in operation. Resource efficiency allows the businesses to optimize usage of raw material with reduced energy consumption as waste output to boost productivity and sustainability (Fiksel, 2006).

Environmental sustainability can be seen in the employment of the cleaner production procedures that are one of the critical approaches to such objectives. The principles of circular economy address sustainability by supporting the recycling programs and remanufacturing practices, and sustainable material acquisition, Ellen MacArthur

Foundation (2013). The transition to circular economy models will allow organizations to cut on carbon emissions as well as improve upon the cost efficiency.

Manufacturing process evaluation runs from extraction of raw material to disposal of the end products through the conduct of Life cycle assessment (LCA) (Hellweg & Canals, 2014). The LCA evaluation process directs the business toward making data-driven decisions on the choice of materials and methods of production and the products' disposal at the end of their lives to minimize the environmental damage.

The implementation of sustainable manufacturing practices creates benefits, and nevertheless, organizations still struggle to attain full environmental efficiency level. The barriers to green technologies are mostly their high start-up cost and strict rules and unwillingness of the staff of an organization to adopt changes (Mazzi et al., 2016). The change to sustainable industry operations is also supported through government policies, technology advancements, and incentives of governmental bodies. Future research should devise effective answers, which combine environmental sustainability practices with technology of advancement for delivery of sustainable production methods.

Environmental sustainability in combination with resource efficiency is required by the textile industry to create sustainable operational successes. Textile manufacturing is an industry that is heavily resource intensive since it requires a lot of water and energy as well as raw materials but gives high levels of waste streams and emissions. Manufacturers should adopt sustainable practices because sustainable practices enable them to maximize resources and minimize the wastage and maximize energy efficiency (Choudhury 2017). The investigation considers the Overall Equipment Effectiveness (OEE) optimization as an environmental sustainability solution that increases machine effectiveness and reduces the usage of resources, maintains the usage of energy expenses on the textile manufacturing operations.

The manufacturing industry benchmarks its resource efficiency by manufacturing products based on minimal use of resources and less ecological damage. The enhancement of resource efficiency comprised three critical approaches, namely, a decrease in waste material and optimization of energy, and -management of the use of circular economy input recycling practices (Ghobakhloo, 2020). Greenhouse gas emissions for industry are huge due to textile manufacturing operations, which are energy intensive in dyeing and finishing and fabric manufacturing. Automation and energy efficient machinery systems that will minimize energy consumptions lead to better production output. By applying lean manufacturing methods such as: Total Productive Maintenance, Just-in-time production organizations can save resources by using the machines at their optimal levels with minimum time wastage (Kumar et al., 2021).

The use of water is one of the aspects that is always crucial in terms of sustainable practice in textile production. An extensive amount of water is used in textile processing operations that operate based on traditional ideas during the coloring and washing processes, this leads to water discharge that comprises of destructive substances. Such practices of sustainable management of water such as the water recycling systems and closed-loop dyeing processes and wastewater treatment technologies assist the industry in reducing the environmental impact (Sharma et al., 2021). The ripple effect of using green dyes and solutions in fiber option will limit pollution levels while fulfilling the product performance standards and the manufacturing efficiency.

The integration of IoT as technology along with AI and predictive systems provides an opportunity for textile manufacturing firms to maximize resource utilization under the industry 4.0 operations. Time-based energy and water usage quantifications using the IoT enabled sensors imply that the textile manufacturers can locate efficiency spots hence to make correctives. Thanks to the AI-based applications for predictive maintenance operators they can reduce machine breakdowns what cause less unexpected stoppages and improve machines' operation effectiveness. Smart technology deployments enable textile producers to establish sustainable data-based production spaces that maximize effectiveness of resources without affecting productivity (Tao et al., 2018).

Environmental sustainability gains of circular economy principles are brought about from the possibility of reducing waste, recovery of materials and extension of product life Cycles. The industry attains greater levels of environmental and social sustainability by implementing sustainable practices in the supply chain and responsible sourcing of raw material that would involve ethical labor practices (Jabbour et al., 2015).

Good corporate governance and regulatory compliance is the main force that steers the textile manufacturers towards sustainable manufacturing practices. Most sanctioned institutions implement strict laws on the environment involving carbon emission placement and the disposal of waste to regulate environmentally conscious industrial activities. Involvement in such environmental regulations contributes to reducing the corporate impact towards the environment and provides the ways for improved market stands and corporate reputation (United Nations, 2015). Manufacturers can be provided with sustainable certification programs like ISO 14001 Environmental Management Systems and OEKO-TEX® Sustainable Textile Production to have access to frameworks to support them to improve their sustainability performance measurements.

Environmental sustainability in combination with resource efficiency ensures the further development of textile manufacturing activities. Textile producers who implement Operational Efficiency Enhancement in combination with environmentally friendly technology applications and the application of circular economics practices, and meet all environmental requirements, will be able to achieve efficiency improvement and reduced environmental damage (Choudhury, 2014). Researchers investigate how the measurement of OEE works towards alignment of sustainable manufacturing goal with operation productivity improvement in textile firms to construct a sustainable resilient textile sector (Kusi-Sarpong et al., 2019).

3 Research Method

3.1 Mixed Method Approach

The research uses a mixed-methods approach for improving textile OEE that includes both quantitative and qualitative information methods of collection. While implementing mixed methods research into Overall Equipment Effectiveness (OEE) one must use both quantitative data for example machine run times, defect rates, production outputs and qualitative data such as operator experiences, interviews with maintenance staff and observations of production behavior to understand and improve manufacturing efficiency (Creswell & Plano Clark, 2018). Quantitative analysis of numerical data analysis methods, together with qualitative information supplied by experts, is combined in the research to come up with a complete OEE evaluation method.

3.2 Theory and Frameworks Related to OEE and Sustainability

Research studies illustrate the relation between OEE relating to sustainability through development of theoretical models between operational efficiency and environmental as well as economic performance. Triple Bottom Line (TBL) framework is one of the mainstream business models that have been deployed in ensuring that there is balance around economic performance and the environment and social elements in operations (Elkington, 1997). When the production improvements are made related to the TBL principles, a sustainable increase in business growth can be accomplished by the managers through enhancements in OEE.

Lean Six Sigma becomes one of the primary frameworks that unite practices of elimination of manufacturing waste according to the lean manufacturing paradigm with Six Sigma quality improvement strategies as described by George (2002). Silent adoption of Lean Six Sigma technology leads to sustainable effects since it reduces time of the machines and streamline production processes with fewer defective products and without wastage of energy and materials.

The Sustainable Value Stream Mapping (SVSM) model harmonizes the lean concepts with sustainability and possesses distinct processes for identifying areas of environmental impact focus and making optimum use of resources (Faulkner & Badurdeen, 2014). Further studies should develop the amalgamation frameworks, in which circular economics will be combined with AI analytics and measurements of sustainability to maximize OEE and environmental performance in the production plants.

For instance, there are several theoretical models and the industrial frameworks that underpin the optimization process of Overall Equipment Effectiveness (OEE) and its sustainability integration to achieve a due operation effectiveness and environmental impact. Manufacturers use OEE as a key measure of performance after its evolution through the Total Productive Maintenance (TPM) to ensure the machinery functions at an effective speed, the quality of the product is maintained (Nakajima, 1988). OEE has been becoming an increasingly science of interest in sustainability relations with the use of Lean Manufacturing in conjunction with the Triple Bottom Line (TBL), Circular Economy (CE), and Industry 4.0. Theoretical frameworks are for the purpose of understanding the way businesses should improve their manufacturing efficiency by pursuing environmental and social agendas.

The basis is set for the OEE measurement and improvement through TPM framework which Nakajima (1988) established. TPM provides equipment reliability and operational efficiency through planned intervention strategies that engage employees with a proactive maintenance mechanism and sustainability growth. TPM has OEE as its core measurement tool for its identification of factors like quality problems, slowdown or unplanned stoppages that hinder production efficiency. Transformational Production Management allows for improving all key OEE parameter scores, as such, higher productivity; with less energy consumption, waste generation and production downtime, towards sustainable industrial operations (Sharma et al., 2021).

Lean Manufacturing is the fundamental strategy that actualizes the correspondence of the OEE optimization and sustainability practices. The Lean philosophy applies the Toyota production system (TPS) principles to eliminate waste (Muda) at the same time it is improving the process flow and achieves maximum value creation (Womack and Jones 1996). The OEE optimization by Lean practices receives improvement because of the Just-In-Time production and the synergy of continuous improvement practices Kaizen and Value Stream Mapping (VSM) for higher usage efficiency of machines and optimized production routes. Lean principles directly lead to sustainability with the dwindling number of resources and optimum consumption of materials with the reduction of carbon emissions which makes these principles a good accompaniment to OEE in textile production (Kumar et al., 2021).

Elkington (1997) expands the traditional production economics to people and environment aspects by embracing People, Planet and Profit sustainability through the Triple Bottom Line framework. The strategy for TBL will to some extent facilitates improvement in all three aspects in people-planet-profit. This method enhances the safety of workers in work sites, reduces workplace strain through predictive maintenance and engages employees. The system employs energy-efficient machines that would reduce the impact on the environment by minimizing waste. The organization makes it profitable to enhance profit as well as contain the cost through optimized production methodology that lessens time lost on the operation. By integrating the OEE measurement with TBL principles, textile manufacturers will be able to operate efficiently as well as be capable of sustaining long-term sustainable practices (Ghobakhloo, 2020).

It is a model presented for industrial resource management that was based on waste minimization, and maximization of recovery output and product life extension as expounded by Ellen MacArthur Foundation (2015). Purpose-driven textile production based on CE concepts allows recycled textile operations as well as factory-scale production and reprocessed products to reduce material gain from the start. The optimization of OEE allows smooth implementation of circular economy due to efficiency reductions and further machine efficiency, as well as waste material maximization that leads to environment-friendly manufacturing processes (Geng et al., 2019).

The traditional manufacturing industry went through some revolutionary changes due to the industry 4.0 technologies such as Artificial Intelligence (AI), the Internet of Things (IoT) and Big Data Analytics. Real-time performance tracking and prophetic up-keep occur due to such modern technologies. The modern technologies increase OEE primarily by the fact that they can reduce the amount of equipment breakdown and optimize the operational settings while improving the production scheduling schemes (Tao et al. 2018). Users can be made sustainable through smart manufacturing since these technologies reduce the amount of energy used and improve supply chain visibility/transparency and data analytics powered sustainable waste reduction. The synergy of the industry 4.0 technology, OEE analysis combined with sustainability standards allows the producers of textile products to achieve maximum advantages from efficiency without harming the environment at a minimal level (Jayal et al., 2010).

Such frameworks provide textile manufacturers with a systematic way of hitting equilibrium in terms of operational efficiency and sustainability alongside business deliverances. Manufacturers can develop sustainable changes to the OEE by systemically integrating the TPM and Lean techniques and sustainability characteristic models such as TBL and CE (Bamber & Dale 2000; Elkington, 1999). Advanced manufacturing tools can be used for joining together various systems. It is realized through a continuous monitoring of data as they come in, the use of forecast to automate proceedings and consequently making things improve continually as far as the effectiveness and reliability of making them is concerned (Lee & Bagheri, 2015; Xu & Xu, 2017).

3.2.1 Justification for Research Method

The mixed-methods approach demonstrates valid use because it measures quantitative performance data together with qualitative analysis for operational inefficiencies. The study uses quantitative research methods to examine OEE elements using production history and downtime records and quality inspection data (Nakajima, 1988). OEE performance trends get summarized through historical data to identify relationships between OEE factors and operational variables including machine utilization, speed losses and maintenance schedules (Montgomery et al., 2021).

Using mixed-methods research, this study seeks to improve Overall Equipment Effectiveness (OEE) in the textile sector of the company. Using some aspects of both quantitative and qualitative methods, the study confirms its findings. A mixed-methods approach allows researchers to look at OEE, analyse figures, and think about how the environment is related to the result. Combining production data, downtime events, and data on quality with quantitative techniques accurately assesses all OEE components. Participants are asked to join in through discussions, interviews, and by observing events, to better understand the observed results. The study makes use of numbers and observation to highlight what each approach is good at and aid in developing strategies for the OEE program in Bangladesh.

3.3 Data Collection Procedure

The study uses different tools, including monitoring and number counting, to estimate the OEE in textile production. Experts in the industry are relied on for their numerical and related knowledge. Creswell & Plano Clark (2018) state that findings are considered reliable and helpful since quantitative methods and qualitative approaches are both used in the study.

3.3.1 Quantitative Data Collection

Most of the research data came from the historical information that the company's specialists on technological updates had compiled. There are 53 production lines managed in the factory, and about 2025 employees carry out jobs in knitting, dyeing, cutting, printing, embroidery, and sewing. The study incorporated statistics and records received from Esquire Knit Composite Limited from a combination of survey, factory log, and production results. All information on availability, efficiency, and quality of machines for 2023 was provided by the Industrial Engineer via the mail and interview. The analysis also checked for reports of machine stops, transformations of machine equipment, manufacturing faults, service manual values, and all the hours the machine was operated during the reporting period. Google Forms was used by the study team to create a survey that was then emailing to the workforce in the knitting, dyeing, cutting, and sewing departments. The responsible manager explained that data was collected by stratified sampling so that the information from all main departments was valuable. I collected the data from the production area and saved it on Microsoft Excel before carrying out the OEE calculations using python tools.

Table 1: Quantitative Data Collection Procedure

Description	Tools and techniques	Collection Date
Historical records (2023)	Data Bank	9-Apr-2025
Production logs	Stratified sampling	9-Apr-2025
Changeover records	Structured Google Form	1-Mar-2025
Machine downtime reports	Structured Google Form	1-Mar-2025
Defect counts	Structured Google Form	1-Mar-2025
Standard Minute Values (SMV)	Structured Google Form	1-Mar-2025

3.3.2 Qualitative Data Collection

This qualitative research analyzes the elements from human along with organizational and operational sectors that impact OEE measures within the textile manufacturing industry. According to Kvale (2007) the subject of qualitative research demands participants who maintain direct field involvement so they can understand the matter from multiple angles. Strategic evaluation and success factor identification and past practice learning benefit significantly from the powerful research method which case analysis represents according to Yin (2018). Qualitative data collection for this research consisted of semi-structured interviews together with 2 production managers and Industrial managers along with focus group sessions and manufacturing plant direct case observation. Two industrial engineers took part in the study because they demonstrated experience in lean manufacturing as well as Total Productive Maintenance (TPM) and sustainability practices. Two online sessions occurred between thirty and sixty minutes long for each participant. Next-level information acquisition involved site observations of operating and suggested maintenance approaches and workflow changes from batch systems to one-piece methods.

Table 2: Qualitative Data Collection Procedure

Description	Tools and Techniques	Collection Date
Semi-Structured Interviews with Production and Industrial Managers	WhatsApp Video Conversation	1-Mar-2025
Focus Group Discussions (2 Participants)	WhatsApp Video Conversation	1-Mar-2025
Case Study Observations	Data Bank	9-Apr-2025

3.4 Data Analysis Procedure

A combination of quantitative and qualitative methods is used to examine Overall Equipment Effectiveness (OEE) from a detailed analysis of available data. They rely on past information after gathering statistics to come up with vital data points like availability and performance and quality (Nakajima, 1988). It relies on specific steps to study the impact of changes in operation factors on the main measures of OEE (Montgomery et al., 2021). A cost-benefit approach allows assessing the costs and financial impact of OEE strategies without harming the company’s profitability, states Boardman et al., (2017). Quali-ty analysis gives information on the effects defects and reworks have on production efficiency, as mentioned by Juran & Gryna (1993).

3.4.1 Quantitative Data Analysis Technique

The factory's general OEE score was investigated using several analytical and evaluative methods with quantitative of data. The overall OEE score was calculated using the percentages for availability and quality formed from examining the data using summarization techniques. Each month's results were analysed to see any developments that influenced OEE levels. By examining Pareto analysis, it was discovered that the biggest inefficiencies were caused by delays in changeovers and the problem of forgotten stitches in the fabric. An analysis of the costs and benefits was done when implementing OEE improvement strategies.

Table 3: Quantitative Data Analysis Tools and Techniques

Quantitative Tools and Techniques Used in This Research	Reason for Using
OEE Assessment and Performance Analysis	To identify areas for improvement in equipment utilization and operational efficiency
Preventive Maintenance	To improve equipment reliability and maintain consistent production flow
Cost of Quality (COQ) Analysis	To evaluate the costs associated with poor quality, such as defects and rework
Cost Per Minute (CPM) Analysis for Efficiency and Waste Reduction	To improve process efficiency and reduce operational expense
SMEP with Digital Kanban for Rapid Changeovers	To minimize the time required for machine setup and changeovers between different products

3.4.2 Qualitative Data Analysis Technique

The research utilizes three fundamental methods to analyse Overall Equipment Effectiveness (OEE) limitations and optimization options. The visualization methods alongside categorization techniques help simplify complex data analysis through systematic qualitative structuring which enables to find operational inefficiencies that produce executable improvements. The analysis tools of flowcharts and Venn diagrams help researchers present adjusted comprehension of their insights effectively. Organizations deploying Conveyor Systems under Lean Manufacturing principles transform their production from batch operations to One-Piece Flow methods which enables streamlined material processes while reducing waste and improving textile factory efficiency. The implementation of this method decreases handling operations which leads to better OEE performance and manufacturing stability. Under the Multiskilling Strategy for Workforce Optimization manufacturers train their sewing operators to operate different machines to create organizations that are more flexible and adaptable. Diversified worker competencies allow manufacturers to decrease labor constraints through optimized resource distribution which enables better workflow transitions for enhanced productivity. Various qualitative methods collectively support lean manufacturing practices so Esquire Knit Composite Limited can reach superior operational efficiency and maintain sustainable production results.

Table 4: Qualitative Data Analysis Tools and Techniques

Qualitative Tools and Techniques Used in This Research	Reason for Using
Visualization and Categorization	To enhance understanding of complex data and processes, enabling quick identification of improvement opportunities
Implementing Conveyor Systems for Lean Manufacturing	To streamline material flow, reduce waste, and improve production efficiency within a lean framework
Multiskilling Strategy for Workforce Optimization	To increase workforce flexibility and adaptability, optimizing labor allocation and minimizing downtime

3.5 Reliability and Validity of Research Method

Proper reliability and validity of the research method are of key importance for keeping credible research findings. To address reliability in this study, this was done by using a structured and consistent data collection strategy so that quantitative and qualitative measurements remained constant throughout different observations and over different periods of time. The use of historical records, production logs and structured surveys thus made it easy to collect high quality quantitative data, while standardized interview protocols were consequent from the qualitative perspective.

Triangulating findings from several different sources helped ensure the accuracy of the findings. The measurement of OEE was based on data gathered from production measurements and former factory records to avoid any bias. At the same time, the qualitative results from interviews, focus groups, and studying cases provided extra detail about where and how the company could improve. The study used the best practices for mixed methods analysis to spot-check the stats with the opinions of experts. Because of this system, the results became less biased and more likely to be generalized.

Further, internal validity was enhanced by controlling factors like the operators' abilities, the frequency of breakdowns of equipment and workflow interruptions. External validity was enhanced by correlating the findings of the investigation to existing theory on OEE optimization, lean manufacturing, and sustainability practices in the textile sector. The integration of both quantitative rigor and qualitative depth guaranteed that the study had a wide implementation of OEE optimization strategies; hence, the results are both valid and applicable within the real-world textile state of making.

4 Result and Analysis

4.1 Quantitative Analysis of OEE Data

4.1.1 OEE Assessment and Performance Analysis of Factory Operations in 2023

To review availability, the study identified times when work was not productive, such as breakdowns of machines, delays with textiles, difficulties with approving merchandizing, cost negotiations, trim shortages, and holding up printing, embroidery, and cutting. To gather performance-related data, things such as capacity hit rates, assessments of skills, machine speed losses, and inefficient balances were considered. Furthermore, data from garments that were not passed quality checks was used to assess every OEE component.

The quantitative data collected for OEE calculations is summarized in Table 5, showing key performance indicators from historical records of 2023 that satisfy research questions 2:

Table 5: OEE Calculation Data (Year of 2023)

Description	Data for one Year (2023)	Details of Data Calculation
Planned Time	284080824.0	Planned Time= Loading Time
Changeover Loss Time	16692156.0	Change Over Loss= No. of Changeovers*Average Changeover Time (2.5 Hours) *Line-wise Average Manpower
Breakdown Time	50609292.0	Breakdown Time= Total Machine Breakdown
Total Down Time	67301448.0	Total Breakdown= Change Over Loss + Breakdown Time

Loading Time (Run Time)	216779376.0	Loading Time = Total Time – Planned Breakdowns
Total Production	13032288.0	Total Production of Full Factory
Average SMV	10.8	Average SMV= Total Produced Minute/Total Production
Defective	1085808.0	Defectives Produced Throughout the Factory
Number of Changeover	2808.0	Number of Changeover= Total Number of Changeovers all over the factory
Produced Min	141066227.9	Sum of Total Produced Min throughout the factory

OEE calculations served as the analysis method for the collected data to evaluate the productive manufacturing time across multiple industries (Nakajima, 1988). OEE is determined using the standard formula:

OEE=%Availability*%Performance*%Quality

The OEE calculation for 2023 was based on multiple parameters, including planned time, changeover losses, breakdown time, and total downtime, as shown in Table 6 that satisfy research question 1.

Table 6: Overall Equipment Effectiveness for the year 2023

Factory 2023 OEE		Calculation Tab for OEE	Additional Terms & Calculations
%A	76.31%	% Availability= (Loading Time – Down Time) / Loading Time X 100%	Loading Time = Total Time – Planned Breakdowns & Changeovers

%P	65.05%	% Performance= (Total Production) / (Run Time X Given Capacity) X 100%	
%Q	91.67%	% Quality= (Amount Produced - Amount Defects - Amount Reworks) / Amount Produced X 100%	Run Time = Loading Time – Unplanned Breakdowns
OEE	45.50%	OEE= %A X %P X %Q	

The observed OEE score came out at 45.50% but this low rating indicates numerous problems with manufacturing performance. The company faced reduced profitability because poor performance levels led to increased costs per minute. Several production inefficiencies reduced the number of output minutes even though the operation maintained a constant input duration which compromised overall productivity.

These insights, visualized in Figure 1, underscore the need for strategic interventions to improve availability, performance, and quality in manufacturing operations.

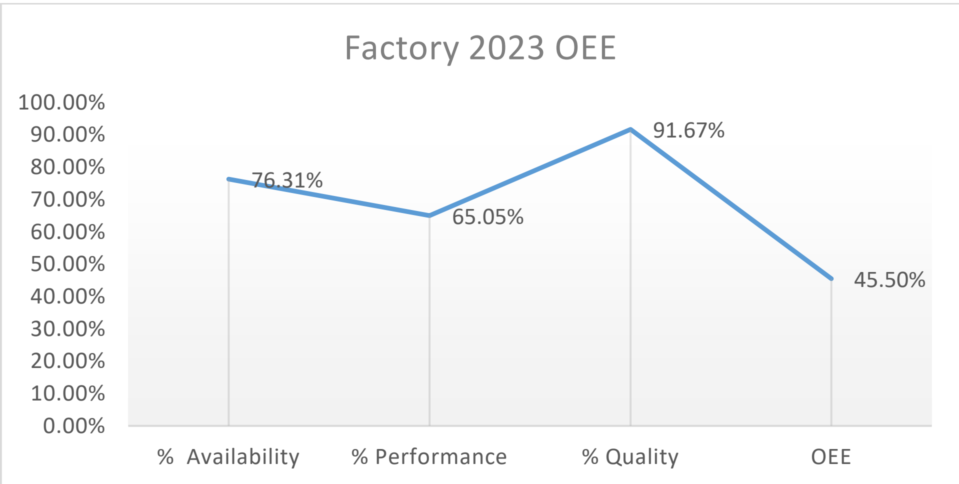


Figure 1: Factory 2023 OEE (Overall Equipment Effectiveness)

The research obtained quantitative information about industrial machine performance by monitoring outputs to measure Overall Equipment Effectiveness (OEE). Structured databases received data acquisition results from machine operational records and production speed points as well as defective output measurements. The data collection procedures generate an extensive database which provides detailed information about the manufacturing processes regarding their operational efficiency and sustainable performance. The following calculation has been done by python software to make a relation among availability, performance and quality.

```
>> % Given Data
>> planned time = 284080824.0; % Planned Time (Loading Time)
>> changeover loss time = 16692156.0; % Changeover Loss Time
>> breakdown time = 50609292.0; % Breakdown Time
>> total downtime = 67301448.0; % Total Downtime (Changeover Loss + Breakdown Time)
>> loading time = 216779376.0; % Loading Time (Run Time)
>> total production = 13032288.0; % Total Production
>> average_smv = 10.8; % Average Standard Minute Value
>> defective = 1085808.0; % Defective Products
>> no_of_changeovers = 2808.0; % Number of Changeovers
>> produced_minutes = 141066227.9; % Sum of Total Produced Minutes
>> % Step 1: Calculate Availability
>> availability = (loading_time / planned_time) * 100;
>> % Step 2: Calculate Performance
>> performance = (produced_minutes / loading_time) * 100;
>> % Step 3: Calculate Quality
>> quality = ((total_production - defective) / total_production) * 100;
>> % Step 4: Calculate OEE
>> oee = (availability * performance * quality) / 100;
>> % Display Results
```

```
>> printf ("Availability: %.2f%%\n", availability);
Availability: 76.31%
>> printf ("Performance: %.2f%%\n", performance);
Performance: 65.07%
>> printf ("Quality: %.2f%%\n", quality);
Quality: 91.67%
>> printf ("Overall Equipment Effectiveness (OEE): %.2f%%\n", oee);
Overall Equipment Effectiveness (OEE): 45.51%
>>
```

4.1.2 Shifting from Breakdown to Preventive Maintenance in Garment Manufacturing

Selecting preventative maintenance is important for the garment manufacturing enterprise, as it improves machine effectiveness and lessens equipment issues and lowers the rate of poor-quality products. In Nakajima’s study, reactive maintenance, known as breakdown maintenance, leads to errors and machines breaking down before they can be fixed, causing many interruptions and rising costs. Since the company has identified that the machines need inspection and training for operators, it will use its preventative strategy by scheduling inspections, overseeing parts, and keeping up with regular check-ups and planned repairs. The current maintenance flow chart for skipping stitch in sewing line is required 58 mins that has shown in the following figure 2 of flowchart.

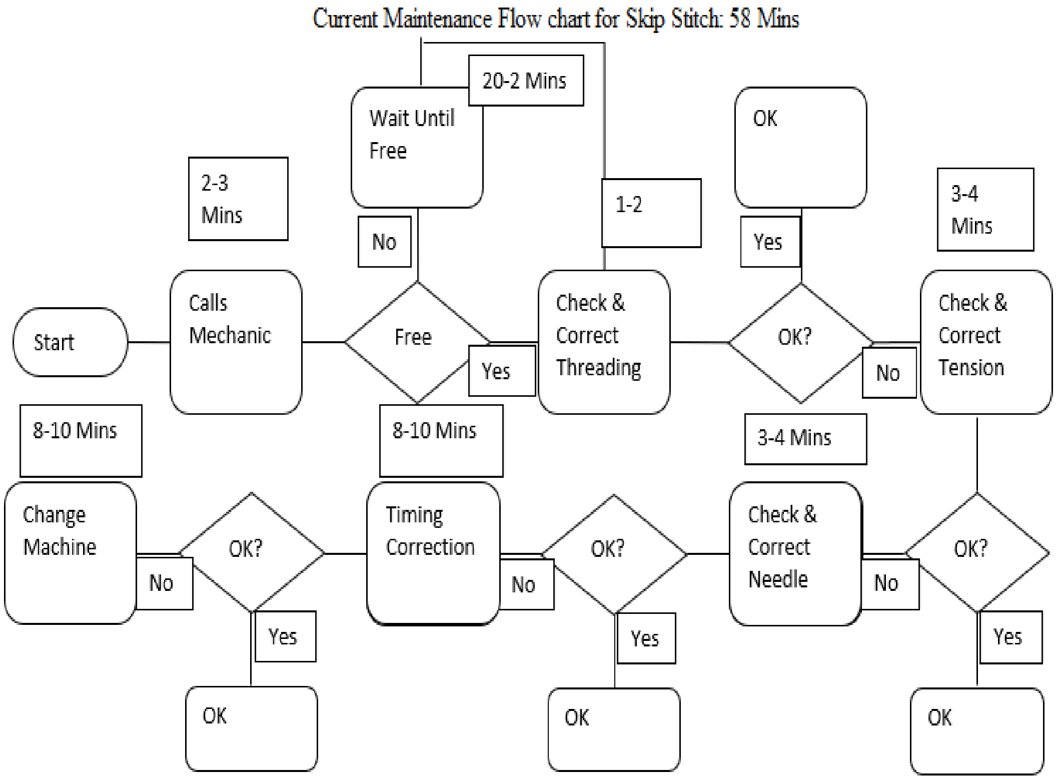


Figure 2: Current Maintenance Flow chart for Skip Stitch: 58 Mins

As part of the new plan, machinery should be maintained routinely with fixed dates for daily lubrication, weekly evaluations of tensioning, and once a month done with heavy cleaning. This will lead to an increase in Overall Equipment Effectiveness (OEE) by making the machines available more often, using their resources effectively, and minimizing faults in garments productions (Sharma et al., 2021). In the current situation, the main major defects skipped stitch of the garments floor are shown in figure 3.

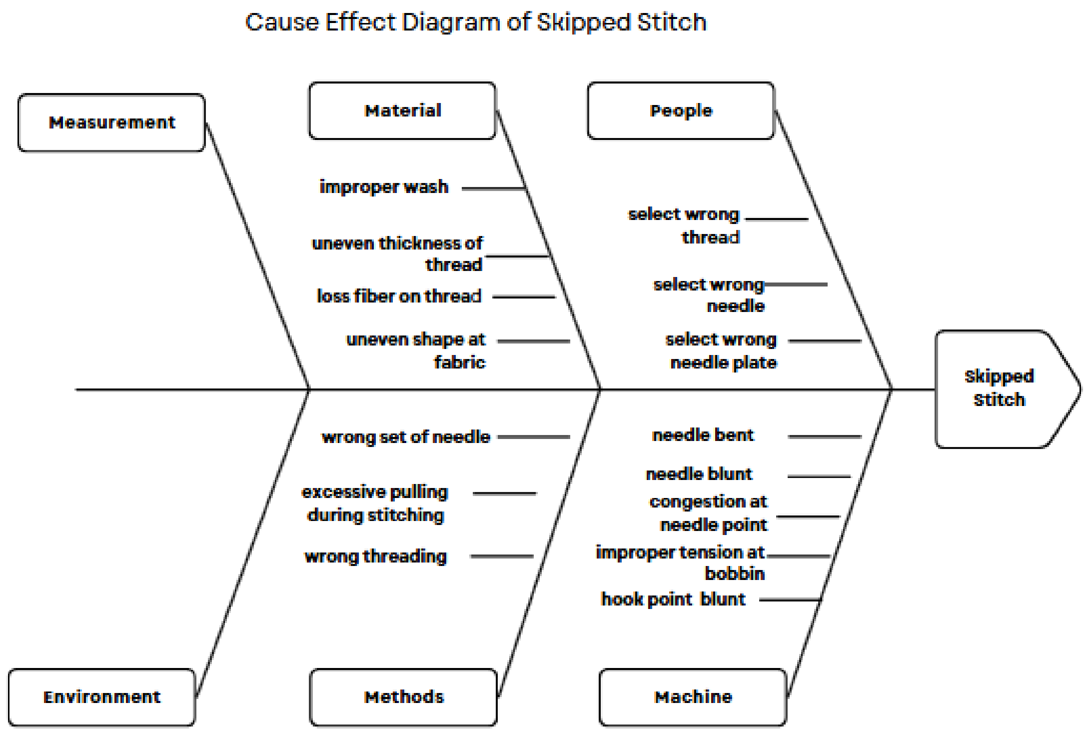


Figure 3: Cause Effect Diagram of Skipped Stitch

Operators and maintenance workers will play an important role in carrying out this system transition. Errors made by operators, lack of proper procedures, and lacking regular maintenance knowledge causes many machines to fail in the garment industry. Training material will be made to educate employees on using the machines and suggest ways to prevent errors and identify potential issues (Ghobakhloo 2020). Being part of regular practice sessions, they turn to cleaning and tension monitoring in their daily lives and rely on specialist support in difficult situations with the equipment. If you carry out regular preventive maintenance, properly train the operator, and treat them as a parent to the machine, you can cut down on maintenance time. Every operator is expected to look after and maintain the machine themselves by performing autonomous maintenance. The operator is the leader of the machine, while the mechanic acts as its doctor. Autonomous maintenance can reduce the downtime of the machine drastically thus reducing the maintenance cost that was shown in the flow chart of the following figure 4.

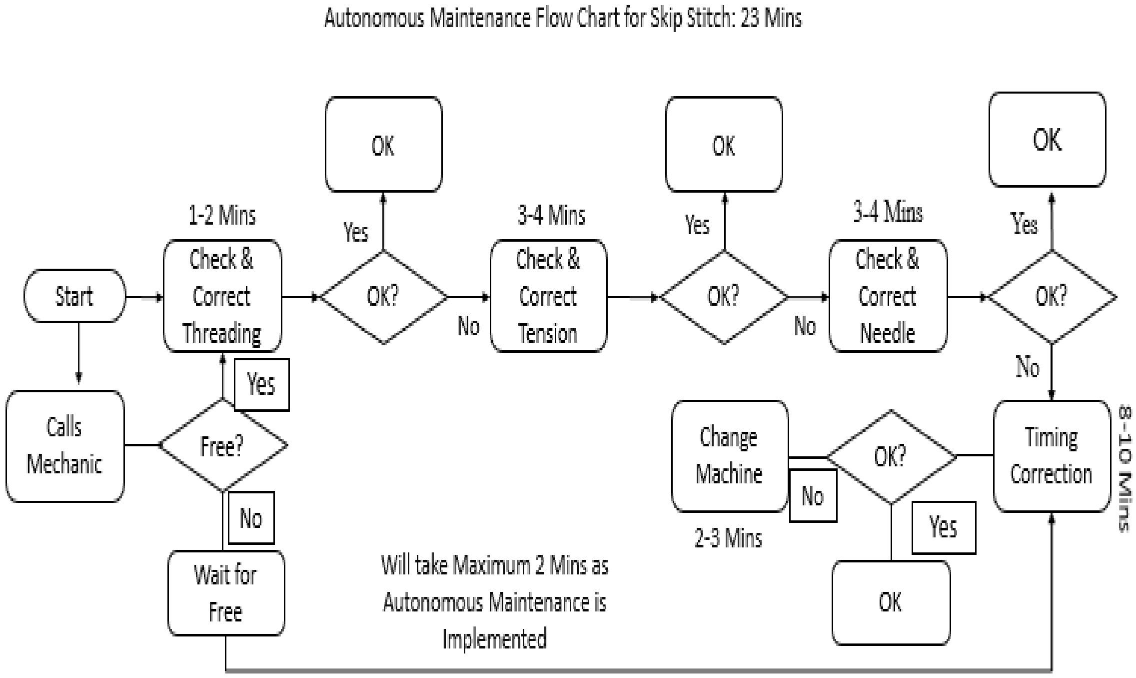


Figure 4: Autonomous Maintenance Flow chart for Skip Stitch: 23 Mins

The changeover process cannot be smooth unless the spare parts are well managed. Before the breakdown, companies were required to purchase spare parts after their machines broke, which led to slow procurement. Taking care of preventative maintenance requires a supply of keys, needles, motors, belts, and all other electronics.

The biggest benefit of preventative maintenance is that it helps prevent unexpected stopping of equipment. Due to former maintenance efforts, companies experienced problems in supply chains, missed their delivery deadlines, and spent more during peak production hours due to frequent machine failures. Ensuring the maintenance schedule is planned with machines by scheduling workshops and nightly inspections to prevent sudden equipment failures and achieve greater efficiency in operations. The company will save money because ongoing maintenance is more valuable than responding to problems in an emergency, which leads to last-minute purchases and higher labor costs (Montgomery, 2020).

In addition to cost reduction the quality of products will enhance because equipment properly maintained by the clothes will complete stitching with accuracy while ensuring low defect rates. Bulk costs from reworking goods result from machines that are not properly maintained since they produce inconsistent stitching and alignment problems and defective final products. Using preventative maintenance will enable the company to deliver better quality products with reduced material waste and satisfied customers who meet all buyer requirements (Juran & Gryna, 1988). By analyzing current spare part management. A proposed pareto chart has been drawn to make significant improvement in productivity and efficiency that is shown in the following figure 5.

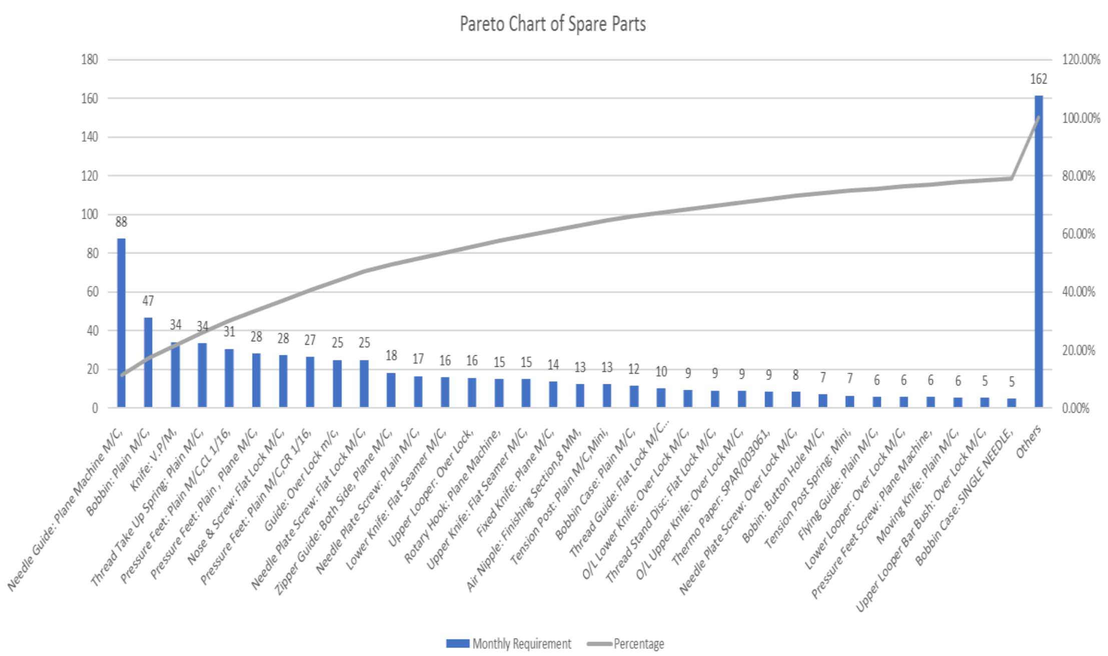


Figure 5: Autonomous Maintenance Pareto Chart for Spare Parts

An inability to manage schedules properly and give adequate training cause employees to work below their potential. As time continues with non-production activities such as setting up machines and solving problems linked to material waiting, the costs of labor rise little by little. To gather data on energy use, electricity, water, and gas resources are constantly monitored throughout the entire textile production process (Sharma et al., 2021). When machinery and equipment are not effective and breakdown often, it causes energy consumption to rise, making the cost per minute go up.

4.1.3 Optimizing Garment Production with Critical Path Method (CPM)

In the garment industry, CPM is often used to plan production in a way that cuts down on delays, helping goods reach the customers early. Using CPM, manufacturers can discover the main tasks and then use resources where they are most needed to reduce delays in production. Since there are multiple steps in garment manufacture, from choosing fabric to finishing it and sending it out, CPM is very important (Khan et al., 2018). With critical path method (CPM), one finds out the key sequences of tasks that are essential for keeping a project on time (Kerzner, 2017). With CPM, manufacturers can produce items more efficiently, fulfilling both demands of the operational context and the quick fashion market (Sarker & Haque, 2020). Net-work diagrams should be used by the team to highlight the connections between various activities. Because of these critical delays in the production schedule, organizations must work on managing resources and preventing any issues (Sharma & Saha, 2015).

Step- 01: Listing all the Activities: The list of all the processes to produce a Polo Shirt SMV is estimated in the following table.

Step- 02: Determining Predecessors & Successors: In the following table successors and predecessors are determined and the time for completing each job is also included. Table 7 applies Critical Path Method (CPM) for optimizing production schedule management and satisfying the research question 3.

Table 7: Standard Minute Value for a Polo Shirt

SL	M/C	Operations	Predecessors	Time

A	H/P	Body mark for placket	-	0.3
B	S/N	Placket rolling & mark with fusing	-	0.6
C	S/N	Placket attach	A, B	0.4
D	4O/L	Shoulder joins with middle scissoring	C	0.6
E	4O/L	Care labels make	-	0.2
F	H/P	Collar mending	-	0.5
G	O/L	Collar service & mark	F	0.3
H	S/N	Placket nose tack & collar tack to body	D, G	0.4
I	4O/L	Collar attach	H	0.3
J	F/L(F)	Neck tape attaches with nose turn	I	0.3
K	S/N	Upper placket close & out top stitch	J	0.6
L	S/N	Lower placket close & out top stitch	K	0.6
M	S/N	Placket box	L	0.5
N	S/N	Neck binding top stitch wd la-bel & mark	M	0.6
O	O/L	Sleeve cuff servicing & cut	-	0.4
P	4O/L	Sleeve cuffs attach	O	0.4
Q	H/P	Sleeve number match	N, P	0.3
R	4O/L	Sleeve attach & placket edge o/l	Q	0.8
S	F/L(C)	Arm hole top stitch	R	0.6

T	4O/L	Side seam	S	0.7
U	S/N	Sleeve In-Out Tack & Placket Security Tack with Care Label	E, T	0.8
V	B/H	Buttonhole (2) with turn	U	0.4
W	F/L(V)	Bottom hem	V	0.4
X	B/A	Button Attach with Button Mark & Close	W	0.7
Y	H/P	Final turn & thread-cut	X	0.4
Total				11.8

Step- 03: Drawing Network Diagram: The network diagram is drawn below according to the data

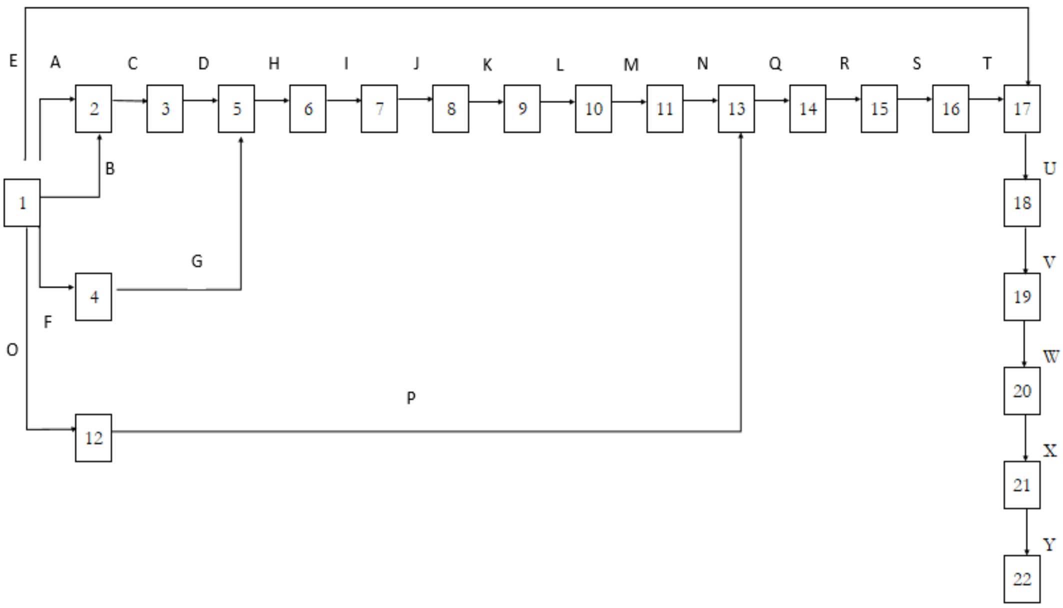


Figure 6: Critical Path Method Analysis for a Polo Shirt

Step- 04: Determining All Possible Paths: After Completing The network diagram determines all alternative paths that can be taken to reach the end of the diagram.

The alternative possible paths can be as follows:

- E-U-V-W-X-Y
- A-C-D-H-I-J-K-L-M-N-Q-R-S-T-U-V-W-X-Y

- B-C-D-H-I-J-K-L-M-N-Q-R-S-T-U-V-W-X-Y
- F-G-H-I-J-K-L-M-N-Q-R-S-T-U-V-W-X-Y
- O-P-Q-R-S-T-U-V-W-X-Y

Step- 05: Identifying The Critical Path: Add up all the times from the table of each process of every path. The path that consumes highest time is the critical path.
The total time of all alternative possible paths are:

- E-U-V-W-X-Y=2.8
- A-C-D-H-I-J-K-L-M-N-Q-R-S-T-U-V-W-X-Y= 9.4
- B-C-D-H-I-J-K-L-M-N-Q-R-S-T-U-V-W-X-Y = 9.7
- F-G-H-I-J-K-K-L-M-N-Q-R-S-T-U-V-W-X-Y= 8.9
- O-P-Q-R-S-T-U-V-W-X-Y = 5.6

So, in our example the critical path time is 9.7. Proper analysis of CPM can reduce the total throughput time.

Succeeding in using the Critical Path Method (CPM) within the garment industry calls for addressing several significant problems. Collecting the necessary time estimates for use in CPM is hard work, limiting how useful the method is. When operations change suddenly and often, keeping the production schedule up to date can be very tough. Whenever there are delays in getting materials, all downstream operations are disrupted because they rely heavily on the supply chain. It shows how important it is to have positive supplier relationships. Sewing and assembly tasks are done by skilled workers, as their speed affects the overall length of the production process. Unexpected things that can affect both the important project schedule and project expenses, for example, when machines fail or there is a power outage, or when customer orders change abruptly (Gunasekaran et al., 2019).

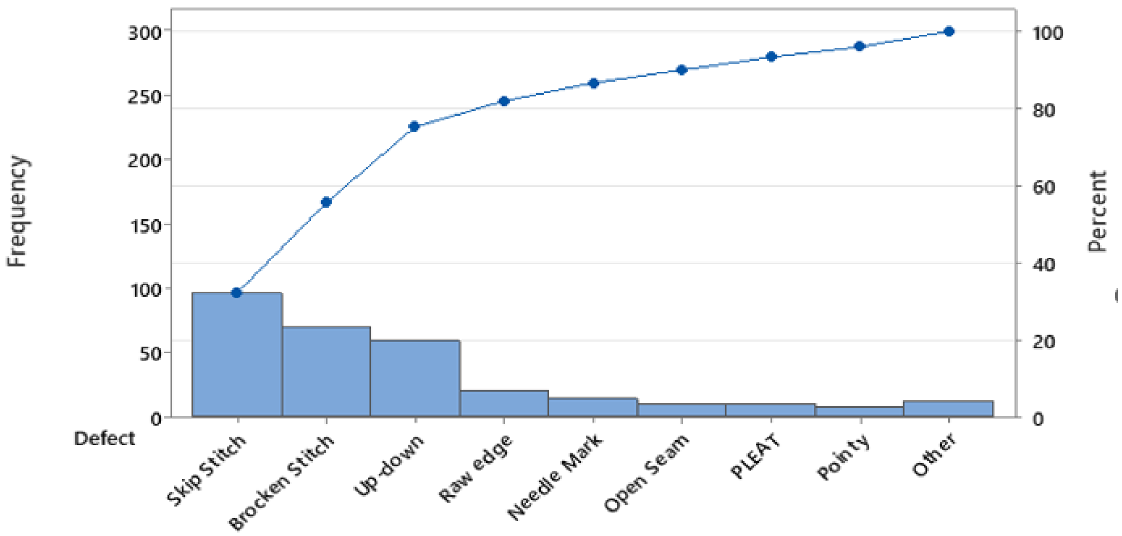
4.1.4 Cost of Quality (COQ) Analysis in Garment Manufacturing

To achieve the right product quality in the garment industry, the sum of all expenses is referred to as the Cost of Quality (COQ). It requires action to prevent defects as well as to find non-conforming issues and resolve any related problems. The funds spent on quality management impact the company's ability to make a profit, its efficiency, and satisfy customers. Market competition is rising all over the globe, so manufacturers of garments need to manage costs and ensure top quality. Juran and Gryna adjusted the COQ model set forward by Feigenbaum (1956) by adding prevention costs, appraisal costs, internal failure costs, and external failure costs. Such organizing of spending stories shows that supporting quality management is a financially beneficial choice and that early spending to prevent issues is better than waiting to reduce costs late (Harrington, 1999). A common analysis in table 8 of a sewing line defect of the product of Polo shirt and data has been taken from historical industry data and the document outlines product flaws to help evaluate quality-based operational issues that satisfy the research question 2.

Table 8: Quality Defects of a Particular Line

Defect	Frequency
Brocken Stitch	70
Open Seam	10
Wavy	2
Skip Stitch	96
Raw edge	20
Pointy	8
Up-down	59
Wrong Label	3
Needle Mark	14
Incorrect Measurement	1
Shearing/Puckering	6
Pleat	10

The Pareto principle (also known as the 80/20 rule, the law of the vital few, or the principle of factor sparsity) states that, for many events, roughly 80% of the effects come from 20% of the causes. A Pareto chart, named after Vilfredo Pareto, is a type of chart that contains both bars and a line graph, where individual values are represented in descending order by bars, and the cumulative total is represented by the line are shown in Figure 7.



Defect	Skip Stitch	Brocken Stitch	Up-down	Raw edge	Needle Mark	Open Seam	PLEAT	Pointy	Other
Frequency	96	70	59	20	14	10	10	8	12
Percent	32.1	23.4	19.7	6.7	4.7	3.3	3.3	2.7	4.0
Cum %	32.1	55.5	75.3	81.9	86.6	90.0	93.3	96.0	100.0

Figure 7: Pareto Analysis Quality of Defects

To prevent defects, organizations invest in staff training, processes designed to stop defects before they happen, checking products supplied, and maintaining equipment. Emphasizing basic sewing, along with cutting and finishing, in garment industry jobs helps to reduce the number of defects and wastage of materials. Khanna (2019) points out that using ISO 9001 and Six Sigma leads to lower failure rates and improved control of defects in organizations. Spending on preventive care during the first period is worthwhile since it stops many breakdowns and operating inefficiencies (Crosby, 1979).

In manufacturing, the nature of testing and inspections carried out at each stage counts as appraisal costs. In the textile business, expenses for appraisal include testing the fabric in the beginning, checking the quality while it is produced, and testing again once finished products are finished. While checking products more intensively raised cost and slowed down the process, reviews helped ensure that hardly any imperfect items were sent to customers (Garvin, 1987).

Inside the factory, internal failures occur when products have defects and this results in rework, a halt in production, additional material and increased downtime for equipment. Erroneous stitching, incorrect sizing, or broken fabric will create delays and increase the expenses involved in making products. When items from the factory fail to meet the standards of quality, they need to be either repaired or scrapped, which raises both material and labor costs.

When products have external failures, the biggest cost for garment manufacturers is that the goods reach their customers being defective. Companies must deal with expenses such as returning products, handling warranty claims, paying customers, reduced revenue, and a damaged brand name. If fast fashion companies exporting products fail to meet the requirements of buyers, orders are canceled, and buyers may fine the company. Those manufacturers who cannot offer quality garments usually lose their customers' loyalty and might not be able to keep their business going.

Using lean manufacturing and tracking defects in real time allows producing higher-quality products that consumers buy, which in turn decreases the need for repairs or replacements (according to Juran & Gryna, 1988). Table 9 analysis repair cost per day of a particular sewing floor and data has been found from the company's historical data and the tool shows machine defect financial consequences which helps organizations prepare preventive maintenance strategies that satisfy the research question 1.

Table 9: Repair Cost Analysis Per Day

Per Minute Salary (TK)			Time Required (mins)to Repair a Defect			Total Repair Cost (Salary/min *Repair Time) TK	Defect Daily	Cost/Daily TK	Cost/Daily $
Operator	Helper	QCI	Operator	Helper	QCI				
1	0.5	1	3	1	0.25	3.75	10800	40500	337.5

The garment industry will achieve reduced Cost of Quality by dedicating efforts to prevention actions rather than reacting to failures. Lower defect rates together with improved cost efficiency result from increased supplier relationship strength while training and automatic quality control systems integration.

4.1.5 Cost Per Minute (CPM) Analysis for Efficiency and Waste Reduction

With the new structure, maintenance staff throughout the company can keep records while also identifying recurring equipment issues and creating better ways to prevent them. According to Ghobakhloo (2020) the company relies on proactive maintenance, rather than reactive methods, to cut costs and boost production while also extending the machines' lives so the company can stay ahead in its industry. The Factory Cost Per Minute (CPM) is calculated monthly by recording total costs, input minutes, efficiency rates, and output minutes.

Cost Per Minute (CPM) Analysis is conducted using the formula:

CPM=Total Cost per Month/Output Minutes per Month

The following table 10 provides a detailed breakdown of the CPM calculation and satisfies the research question 1:

Table 10: Factory Per Month Average Cost Per Minute (CPM)

Total Cost /Month	Input Minute/Month	Present Average Efficiency	Output Minute	Cost Per Minute
$658789.68	35229395	45.50%	16029374.73	$ 0.455

This calculation helps assess cost efficiency and identify factors contributing to increased production expenses. The identification of waste occurs through comparing labor expenses with material costs and energy usage between various time intervals.

4.1.6 Implementing SMEP with Digital Kanban for Rapid Changeovers

SMEP benefits small and medium garment businesses by reducing setup time for machines, making production smooth, and cutting downtime and increasing flexibility in garment processing. SMEP's techniques, borrowed from Shigeo Shingo's type of SMED in 1985, make it possible to optimize sewing adjustments for both garment and material changes in less than ten minutes. For ensuring Single Minute Exchange of Die (SMED) the industry must follow the digital kanban board of changeover and must fill the form as per the designated department that is shown in figure 8.

Responsible Section	Planning			IE		QA Heads		Production Manager		Store	Mechanics	Technician		Finishing In charge
Before	4 Days			3 Days	2 Days	2 Days		2 Days		2 Days		3 Days		2 Days
Changeover Date	Buyer & file	Allocated Qty	Line no	Layout	Critical operation Training	PP meeting	Cuff, Collar, Drawstring approval issue	Input	File & trim Card	Trims & accessories	Machine ,Guide, folder	Finish Pattern	Sample making by line chief	Folding Approval

Figure 8: Digital Kanban Changeover Board

Traditional garment factories spend between 30 minutes to several hours for setup procedures at sewing machines and cutting tables and pressing stations which results in high non-productive time and decreased efficiency and increased production costs. According to (Monden, 2011) through SMEP manufacturers can divide their production process into internal machine-dependent tasks and external running tasks which together minimize the total downtime.

SMEP improves machine setup, speed of attaching tools, visual programming, and effective tool placement to ensure there are no stops in producing goods (Liker, 2004). Frequent style changes in the market and fast fashion require the garment industry to improve the time it takes to switch machines, as noted by Womack & Jones (1996). Because of SMEP, apparel can be made faster, with lesser amounts in stock, more machinery being used, and greater capacity to change manufacturing on the fly, so it remains a helpful approach in efficient producing (Shah & Ward, 2007). Results from the application of SMEP only last if workers accept the new methods and if there is ongoing training and tools are regularly updated. As a result of following SMEP, apparel companies increase how much they produce and make their equipment more effective while fulfilling any shifts in production (Ohno, 1988). It is possible to increase significant efficiency by following digital changeover board. The following table 11 shows how lean manufacturing principles like SMED improve efficiency and satisfy the research question 3.

Table 11: Efficiency Gain in Terms of Changeover Reduction

Description	Value
Total Number of Line	53
Total Manpower	2025
Avg Changeover/Month /line	4.92
Total Changeover /Month	261
Average Change over Time (Hours)	2.59
Monthly Average Efficiency	55%
Average Change over Time (Minutes)	1367621
Monthly Growth (Minute)	752192

Total Available min	30375000
Monthly produce min	16706250
Increased Produce min	17458442
Increase Efficiency	57%
Efficiency Gain	2%

4.2 Qualitative Analysis of OEE Data

4.2.1 Qualitative Insights from Plant Managers on OEE Challenges in Textile Manufacturing

The analysis identifies tested OEE optimization practices, which the researcher will employ to develop performance improvement recommendations for textile manufacturing facilities. Table 12 presents qualitative insights about operational challenges which include details on causes of downtime as well as performance problems and defect patterns and satisfy the research question 2.

Table 12: Interview Data of OEE from Responsible Plant Manager

Timestamp	3/1/2025 18:12:28	3/2/2025 7:52:19
Name	Md. Osman Goni	Vaskar Malakar
Gender	Male	Male
Age	31	32
Designation	Deputy Manager	Assistant Manager
Name of the Industry	Esquire Knit Composite PLC	Esquire Knit Composite PLC
Type of the Business	Garments Exporting	Garments Exporting
Country	Bangladesh	Bangladesh
First Option is availability Losses	Input gap	Input gap
Average Input Gap Per Day	2 hours	1.25 hours

Choose the most frequent reason for Input Gap (You can select one or multiple options)	Cutting, Dying	Cutting, Printing, Embroidery, Dying, Knitting
Average Downtime for the above point mentioned in Questions 1	10%	81 hours
Second Option is Performance Loss		
Choose the most frequent reasons for performance losses	Machine Breakdown	Jumper/Floater Operators not available, No Proper Plan, Extra Working Hours, Machine Breakdown
Average Skill Operator of Each Line	20	40%
Percentage of Skilled Operators per line in terms of grade (A, B, C, D)	50%	A-25%; B-40%; C-35%
Number of Layout Per Day in each line	1	0.095
Number of Changeover Per day	5	1.04
Capacity Hit Rate in Average		Option 1
Plan Accuracy in Per day and Month		Option 1
Number of Jumper/Floater Operators in Per line	1	0
Average absenteeism percentage %	5.00%	8.52%
Third Option is Quality Losses		
Percentage of Sewing Defect Rate	8.00%	12.32%

Percentage of Finishing Defect Rate	5.00%	7.41%
Percentage of Textile Defect Rate	10.00%	6.66%
Percentage of Printing and Embroidery Defect Rate	9.00%	4.20%
Average Percentage of Sewing Endline and Inline Defect	7.00%	12.22%
Average Percentage of Rejection Rate	1.00%	3.23%
What is the most frequent defect	Brocken Stitch	Brocken Stitch, Wavy, Skip Stitch, Up-down, Wrong Label, Needle Mark, Shearing/Puckering

4.2.2 Transitioning from Batch Production to One-Piece Flow: Implementing Conveyor Systems for Lean Manufacturing at Esquire Knit Composite

The present manufacturing process at Esquire Knit Composite functions based on traditional batch production methods which handle bulk garment processing before proceeding with additional stages. Through this method Esquire Knit Composite ends up with excessive WIP inventory and extended lead times as well as irregular quality standards and production blocking. Esquire Knit Composite adopts the Lean Manufacturing (One-Piece Flow) system and conveyor system to surmount operational deficiencies. According to (Womack & Jones 1996) production efficiency and product quality enhancement will be achieved through this transition by enabling continuous garment movement between all production stages without production delays.

In the new design, assemblies are conveyed from cutting stations to sewing and on to finishing before a quality test by an automated system. As transport of the garments is automated, items are moved efficiently and at the same speed, so the production process stays steady (Liker, 2004). Keeping the layout as either U-shaped or in a straight line improves the movement of materials and ensures that workers do not touch the items more than necessary (Monden, 2011). The purpose of the conveyor belt is to improve efficiency, cost savings and energy savings that are shown in figure 9.

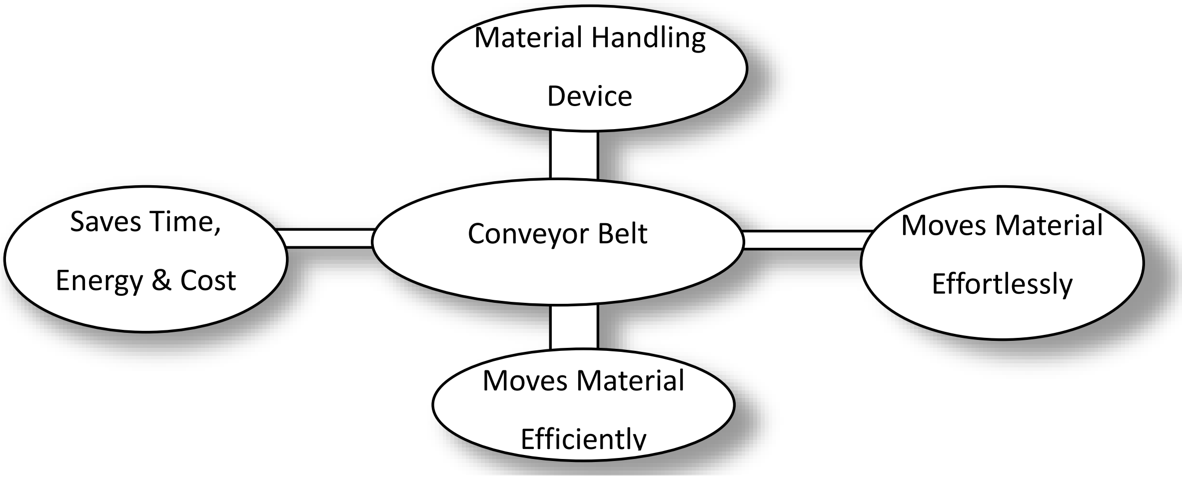


Figure 9: Conveyor Belt Mechanism

Its main benefit is that a conveyor-based One-Piece Flow system cuts down the time it takes to produce items. Goods await completion of the batch before they can pass on to the next phase of production. Because of the constant flow of the conveyor system, fast fashion businesses can meet customers' expectations quickly (Shingo, 1989).

Quality improvement serves as a significant advantage of this method. The analysis of defects happens too late during batch production which results in extensive material loss through rework and resource use. The system will enable real-time detection of defects at each production point through its integration of One-Piece Flow with conveyor technology. re

Using automated conveyors, the company can reduce pauses in the process and time spent on handing out materials to workers. Currently, the time it takes for workers to handle clothes and organize piles results in inefficient use of time and greater strain on the workers. The automated conveyor helps with automating transit of garments, allowing the operators to focus on their work full time. The company will ensure its employees are trained in various steps of the process so they can move around more freely. Allowing cross-training among members of the production team will result in more flexible operations and an equal spread in workload distribution, as stated by Shah and Ward (2007).

To maximize the use of floor space, Esquire Knit Composite will use its One-Piece Flow system and conveyors. The large space needed for WIP in batch production means that the entire production process becomes less efficient. A conveyor system installation in the factory can allow more space for new production areas by reducing storage requirements (Ohno, 1988).

There are a few hurdles when it comes to changing from batch production to One-Piece Flow with conveyors, yet using the system can be very beneficial. The main reason for this is that most workers and supervisors are reluctant to switch their usual ways of producing. Taking advantage of lean manufacturing and conveyor operation, the organization is planning to arrange training for its employees and sessions to help them understand the benefits of these approaches (Spear & Bowen, 1999).

Line balancing becomes a major challenge for industries in manufacturing. As garments move through the conveyor system consistently, in-consistency among stations leads to slowdowns, bottlenecks, and wasted time for the workers. Takt time defines when one unit of the product should be produced to meet demand. Analysis of demand by the company will help make sure employees are working at the optimal speed at every station for seamless garment movement throughout the production line. As the existing layout requires more throughput time so the company should go for single-piece flow production with a conveyor system. The comparison of throughput time is shown in figure 10.

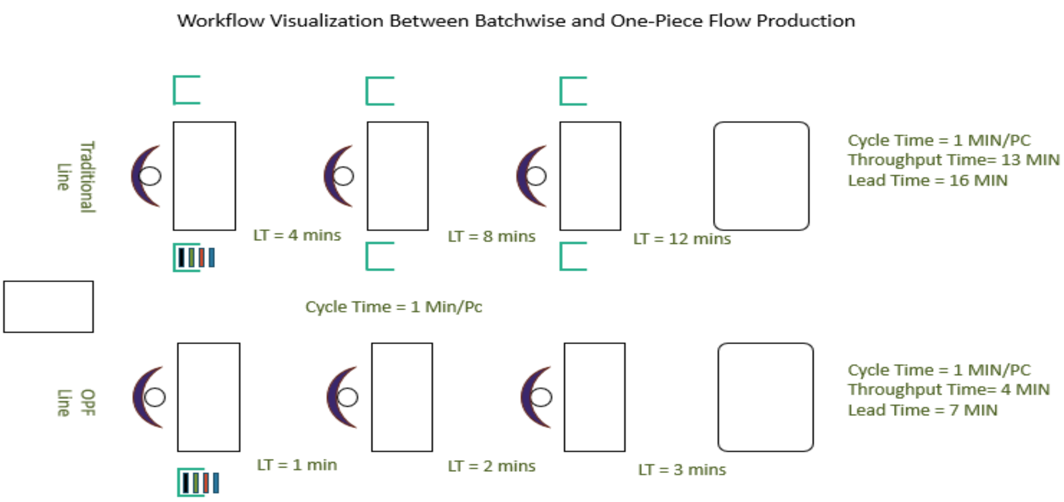


Figure 10: Workflow Visualization between Batch Wise and One-Piece Flow Production

4.2.3 Implementation of Multiskilling Strategy for Workforce Optimization in Garment Sewing Operations

Lean manufacturing is implemented in the garment sewing area by having sewing operators do more than one task during production, not just one. When using standard factory models workers only use one machine, for example, overlock, flatlock, or button-attaching, and this means there are processing delays if the factory's production needs change. If employees are trained in various areas, the factory can boost its productivity and stay flexible in their production lines (Womack & Jones, 1996). Fast fashion operations and demand-based manufacturing benefit from this strategy since it enables rapid changes to styles in production. Managed through multiskilled operators these employees can fill vacancies at different workstations to maintain smooth factory operations despite equipment failures or employee absences. Step by step for multiskilling is given below:

Listing all the common products that are produced by the factory

↓

Taking the budget of total amount of manpower in the line

↓

Making a layout paper of each category of above listed products within the budgeted manpower

↓

Listing how many operators required machine-wise to complete the layout

↓

Listing the Highest and the lowest requirement of operators per machine category

↓

Drawing a Venn Diagram according to the rules below

The importance notes to be maintained for example whose operator process SMV is 0.5 or above, need to give training other item same process SMV. For instance, in polo shirt, collar join process SMV 0.65, so in jacket need to give training zipper join whose SMV 1.00. But whose operator process SMV 0.4 or below, trying to give training in such a way, so that operator can do multitask at a time. The skill requirements for various product categories are displayed in Table 13 as the basis for workforce optimization through the development of skill matrices and satisfying the research question 3.

Table 13: As Per Product Category Line wise Skill Requirement

Product	SN	OL	FL	KS	BH	BT	BA	Total
T-Shirt	9	13	4	1	1	1	1	30
Band Collar Polo	19	5	2	1	1	1	1	30
Hoodie Jacket	9	12	5	1	1	1	1	30
Joggers	9	11	6	1	1	1	1	30
Highest	19	13	6	1	1	1	1	42
Lowest	9	5	2	1	1	1	1	20

Familiarity with many sewing procedures allows workers to enhance their abilities and spot and address any poor quality in partially or finished goods. When workers are trained in multiple skills in the garment industry, their job satisfaction improves, they have more opportunities for promotion, and they usually show greater interest in their jobs, lowering turnover (Shah & Ward, 2007). Garment manufacturing companies must invest time and funds in employees' training and expect them to embrace multiskilling. Leaders are required to set and check work tasks carefully to support the transition between each task or stage of production (Ohno, 1988). Even though it may take some time to implement, having multi-skilled staff with high production levels brings more benefits because it is an essential approach to manufacturing garments (Monden, 2011). For creating skill matrix, the following Venn diagram steps should be followed

Making a circle for each machine category

↓

The area of the circle indicates the total number of operators required for the machine category

↓

The common area means the multiskilled requirement

↓

The area that is not common means the pure skill of the machine

↓

The minimum number of operator requirements is the pure skill requirement for the machine

↓

The highest number of operator requirements is the total skill requirement for the machine

↓

Fixing the number of Jumper operator in the line

↓

Calculating the number of multi-skilled operators considering the above rules

A Venn diagram demonstrates graphically how multiple sets connect with each other. The diagram includes overlapping circular shapes that represent:

- Each circle represents a set.
- Elements that are in common exposure between sets are shown in the shared sections of Venn diagram visualization.
- Each element which exists solely within one set appears in the non-overlapping space of the diagram

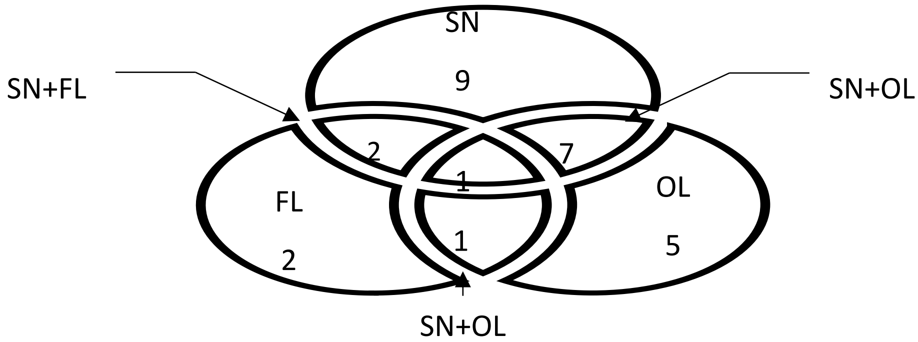


Figure 11: Venn Diagram for Skill Matrix Evaluation

4.3 Comparative Analysis Between Industry Standards and Current Performance

The comparative analysis between Esquire Knit Composite Limited's performance and global industry standards illustrates a significant transformation in operational efficiency following the implementation of lean manufacturing and autonomous maintenance strategies. Previously, the factory's OEE stood at 45.5%, with critical underperformance in performance (65.05%) and availability (76.31%) components, far below the industry benchmarks of 95% and 90% respectively (Nakajima, 1988; Vorne Industries, 2023). However, if the adoption of process improvements—such as proactive and autonomous maintenance, lean line balancing, and the integration of conveyor-based One-Piece Flow production measurable increase in production efficiency has been recorded. Monthly changeovers, averaging 261 across 53 lines with over 2.59 hours per changeover, have now been streamlined, contributing to a notable reduction in downtime. The average changeover time, once totaling 1,367,621 minutes per month, has been reduced, and production output has increased from 16,706,250 to 17,458,442 minutes monthly. This operational shift improved factory efficiency from 55% to 57%, indicating a 2% gain that directly translates into OEE improvement. The recalculated OEE reflects this progress, rising from 45.5% to approximately 57.7%, bringing Esquire Knit Composite significantly closer to industry standards. These improvements will confirm that the applied methodologies are not only effective in reducing losses but also in optimizing manpower utilization and maximizing output from available minutes. When compared with the global OEE benchmark of 85%, the new OEE figure demonstrates that although further optimization is required, the strategic changes have delivered a substantial leap in performance and laid a strong foundation for sustained operational excellence. The factory performance metrics benchmarked against worldwide standards serve as guidelines for developing strategic plans in Table 14 and satisfy the research question 3.

Table 14: Comparison Table Between Industry Standards and Current Performance

Metric	Industry Standard	Before Improvement	Estimation After Improvement	Performance Gap (Post-Improvement)
Availability (%)	≥90%	76.3%	85.0%	-5%
Performance (%)	≥95%	65.0%	73.0%	-22%
Quality (%)	≥99%	91.7%	93.0%	-6%
Overall OEE (%)	≥85%	45.5%	57.7%	-27%
Efficiency (%)	≥85%	55.5%	57.0%	27%
Avg Changeover Time (min)	≤30–60 (lean target)	1367621 total/month	Reduced	Improved
Monthly Produced Minutes	—	16,706,250	17,458,442	752,192

5 Findings and Discussions

5.1 Contribution of Mixed-Methods Analysis to Understanding OEE

A mixed-methods analysis was essential for obtaining detailed knowledge about Overall Equipment Effectiveness (OEE) at Esquire Knit Composite Limited through the fusion of quantitative measurements with qualitative investigative findings. Data evaluation provided an exact representation of availability and quality and performance metrics which exposed a 45.50% total OEE rating deficiency. Primary qualitative data collection methods delivered the fundamental explanations of operational inefficiencies through insights obtained from employee meetings and representative group analyses and single-case studies. Combining quantitative and qualitative data methods produced an extended analysis which determined both operational performance weaknesses and location-oriented solutions. Employee insights allowed the implementation of One-Piece Flow production through a transition from batch processing and confirmed that autonomous maintenance practices lowered system downtime effectively. OEE optimization achieved compatibility with sustainability targets because researchers applied life cycle assessments and cost-benefit analysis to ensure environmental sensitivity and cost-effectiveness in all improvements. The combined use of quantitative and qualitative data methods generated an intricate view of operational issues which led to the creation of functional and enduring manufacturing efficiency strategies.

5.2 Implications of Findings

The research results create multiple significant implications for textile manufacturing operational and strategic management referring specifically to Esquire Knit Composite Limited. The OEE outcome of 45.50% indicates significant operational improvements should take precedence because they would enable machine downtime reduction and allow performance optimization as well as product quality enhancement. Insufficient productivity stems from machine breakdowns which happen often and prolonged process changes and excessive product failures. Preventive and autonomous maintenance systems offer vital importance because they significantly decrease equipment downtime while enhancing total reliability. The research proved that One-Piece Flow along with skill matrix development tools employed through lean manufacturing multiply operational efficiency while optimizing workforce allocation and lowering waste production. The combined power enables operations to become smarter and data-driven, which enhances their performance during changing ground circumstances. The strategy relies on OEE optimization as a tool to achieve sustainability targets because better machine efficiency drives decreased energy use and decreased emissions and waste production. Organizations that implement sustainable practices obtain a competitive market position because global consumers increasingly value sustainability. The research evidence demonstrates the necessity of building a complete textile manufacturing operation management system that simultaneously improves technology while training workers and protecting the environment.

5.3 Limitations of the Research

Several constraints affect the results presented in this study despite its broad scope. The investigation focused exclusively on Esquire Knit Composite Limited as a single case which reduces the potential application of its results to other textile operations throughout Bangladesh or worldwide. The information has specific links to this manufacturing site yet does not show how alternative operational settings could perform. The mixed methods work provided a comprehensive view, but small quantitative interview sample restricted the number of collected in-depth findings from diverse sources. The historical data availability depended on the company records, but it could lack complete operational reality representation due to potential reporting biases. Even though the study focused mainly on manufacturing operations there is no mention of supply chain or customer satisfaction factors which could impact Overall Equipment Effectiveness (OEE). The research limitations create opportunities for future work to conduct multiple factory-based research and expand sustainability evaluations and digital transformation investigations in textile manufacturing.

6 Conclusions and Recommendations

The research served to discover textile industry OEE optimization possibilities using mixed research methods and focused on Esquire Knit Composite Limited in Bangladesh. The research aimed to analyse impact factors on OEE performance along with lean manufacturing technology capacity alongside sustainable operational strategies that increase efficiency.

The research utilized a mixed-methods design structure to combine performance statistics with professional insights obtained from production managers as well as machine operators and maintenance staff. The research methodology allowed researchers to grasp the multiple influencing variables behind OEE measurements in a comprehensive way. Performance data along with defect rates gained from the quantitative assessment revealed human and organizational challenges such as operator training deficiencies and employee disengagement alongside communication problems between organizational departments. Hybrid perspectives within the study guaranteed that recommendations discovered from research combined both relevant information with foundational evidence.

The main research conclusion emphasizes that organizations need to abandon their traditional maintenance systems because they should implement preventive and autonomous maintenance approaches instead. The conducted research revealed that equipment downtime because of failure problems becomes reducible by implementing scheduled servicing methods alongside sensor-based real-time monitoring and operator-driven maintenance practices. The adoption of autonomous maintenance practices reduced the maintenance times for skipped stitch issues from 58 minutes to 23 minutes. The necessary change involves both technical implementations and cultural development which enables the staff to take ownership of machinery health.

The One-Piece Flow production model stands out as a lead method during lean manufacturing adoption to reduce waste and shorten lead times while improving product quality. Through conveyor-based one-piece flow operations the organization achieved operational streamlining and reduced WIP inventory levels and enabled instant quality checks. The organization becomes more market-demand responsive while customer satisfaction improves through these modifications. The implementation of lean systems demands proper training programs along with process redesign and change management approaches to overcome worker opposition to new methods.

The company must invest in Industry 4.0 technologies so they can make decisions based on data. Research confirms that these new technologies can deliver operational changes which lower environmental effects even though Esquire Knit Composite Limited has not implemented them yet. The digital tools help organizations achieve sustainability goals through energy efficiency improvements and waste reduction and equipment life extension because these factors matter to competitive businesses in the modern global economy.

Human resources benefit from research that emphasizes both employee development and skill matrix programming for multi-skilling programs. Multiple production skill training of workers enables better line balancing and shorter waits between tasks and improves facility flexibility. Lean systems require continuous maintenance of process flow which makes this matter critical. Delivering knowledge and empowering tools to workers improves both productivity and creates innovation which develops a proactive work environment.

Organizations need to derive their OEE improvement plans from overall sustainability frameworks according to research findings. The study asserts organizations need Life Cycle Assessment (LCA) and cost-benefit analysis integration in their decision processes to assess operational changes through dual financial and environmental evaluation. Installing real-time energy tracking systems with energy-efficient machines results in simultaneous operational cost reduction as well as decreased carbon emissions. By following environmental certification programs such as ISO 14001 along with OEKO-TEX® standards companies improve their market position as well as brand image.

Successful execution of these recommendations needs both dedicated leadership support and multi departmental uniting of efforts. The top leadership needs to drive change by providing specific goals and proper resources and maintaining ongoing progress checks. The permanent success of OEE optimization depends heavily on having prepared organizations with robust digital systems and skilful staff members who maintain flexible workplace cultures.

Improving OEE in textile manufacturing needs organizations to adopt an all-encompassing integrated system. Organizations obtain major manufacturing performance improvements through integration of lean practices with digital technologies and skilled human capital together with sustainability frameworks while reducing operational expenses. This approach lets businesses defend themselves against global market competition through enhanced efficiency and resilience. The research findings together with suggested recommendations guide Esquire Knit Composite Limited and comparable organizations on how to initiate their path toward sustainable operational excellence and financial success.

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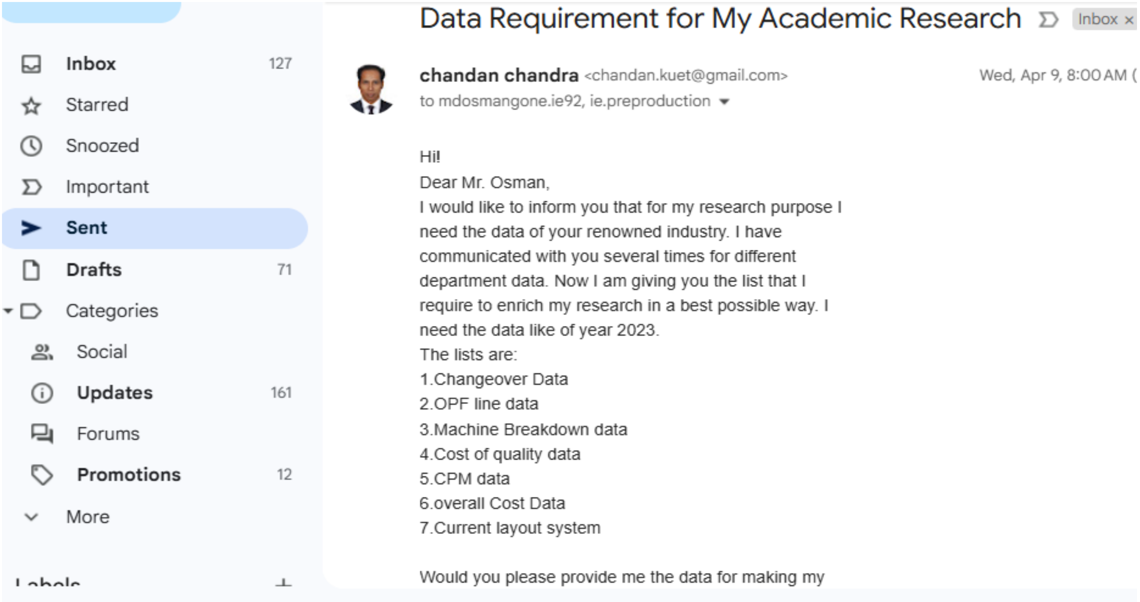
Appendices

Appendix 1. Data Collection for OEE

Timestamp	3/1/2025 18:12:28	3/2/2025 7:52:19
Name	Md. Osman goni	Vaskar Malakar
Gender	Male	Male
Age	31	32
Designation	Deputy Manager	Assistant Manager
Name of the Industry	Esquire Knit Composite PLC	Esquire Knit Composite PLC
Type of the Business	Garments Exporting	Garments Exporting
Country	Bangladesh	Bangladesh
First Option is availability Losses	Input gap	Input gap
Average Input Gap Per Day	2 hrs	1.25 hrs
Choose the most frequent reason of Input Gap (You can select one or multiple options)	Cutting, Dying	Cutting, Printing, Embroidery, Dying, Knitting
Average Downtime for the above point mentioned in Questions 1	10%	81 hrs
Second Option is Performance Loss		
Choose the most frequent reasons for performance losses	Machine Breakdown	Jumper/Floater Operators not available, No Proper Plan, Extra Working Hours, Machine Breakdown
Average Skill Operator of Each Line	20	40%
Percentage of Skilled Operators per line in terms of grade (A,B,C,D)	50%	A-25%; B-40%; C-35%
Number of Layout Per Day in each line	1	0.095
Number of Changeover Per day	5	1.04
Capacity Hit Rate in Average		Option 1
Plan Accuracy in Per day and Month		Option 1
Number of Jumper/Floater Operators in Per line	1	0
Average absenteeism percentage %	5.00%	8.52%
Third Option is Quality Losses		
Percentage of Sewing Defect Rate	8.00%	12.32%
Percentage of Finishing Defect Rate	5.00%	7.41%
Percentage of Textile Defect Rate	10.00%	6.66%
Percentage of Printing and Embroidery Defect Rate	9.00%	4.20%
Average Percentage of Sewing Endline and Inline Defect	7.00%	12.22%
Average Percentage of Rejection Rate	1.00%	3.23%
What is the most frequent defect	Brocken Stitch	Brocken Stitch, Wavy, Skip Stitch, Up-down, Wrong Label, Needle Mark, Shearing/Puckering

Figure 12: Data Collection From Survey By Google Form



Inbox 127
Starred
Snoozed
Important
Sent
Drafts 71
Categories
Social
Updates 161
Forums
Promotions 12
More

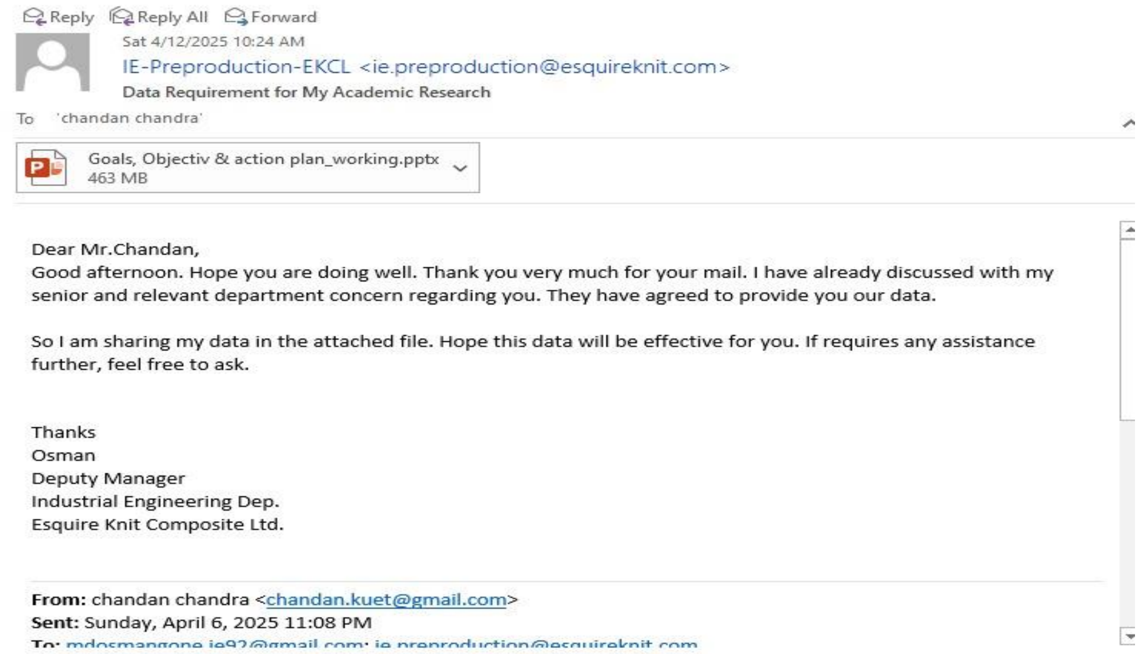
Data Requirement for My Academic Research Inbox ×

chandan chandra <chandan.kuet@gmail.com> Wed, Apr 9, 8:00 AM (
to mdosmangone.ie92, ie.preproduction

Hi!
Dear Mr. Osman,
I would like to inform you that for my research purpose I need the data of your renowned industry. I have communicated with you several times for different department data. Now I am giving you the list that I require to enrich my research in a best possible way. I need the data like of year 2023.
The lists are:
1.Changeover Data
2.OPF line data
3.Machine Breakdown data
4.Cost of quality data
5.CPM data
6.overall Cost Data
7.Current layout system

Would you please provide me the data for making my

Figure 13: Data Collection for Single Piece Layout System



Reply Reply All Forward
Sat 4/12/2025 10:24 AM
IE-Preproduction-EKCL <ie.preproduction@esquireknit.com>
Data Requirement for My Academic Research
To 'chandan chandra'

Goals, Objectiv & action plan_working.pptx
463 MB

Dear Mr.Chandan,
Good afternoon. Hope you are doing well. Thank you very much for your mail. I have already discussed with my senior and relevant department concern regarding you. They have agreed to provide you our data.

So I am sharing my data in the attached file. Hope this data will be effective for you. If requires any assistance further, feel free to ask.

Thanks
Osman
Deputy Manager
Industrial Engineering Dep.
Esquire Knit Composite Ltd.

From: chandan chandra <chandan.kuet@gmail.com>
Sent: Sunday, April 6, 2025 11:08 PM

Figure 14: Data from Esquire Knit Composite Limited for OEE Calculation

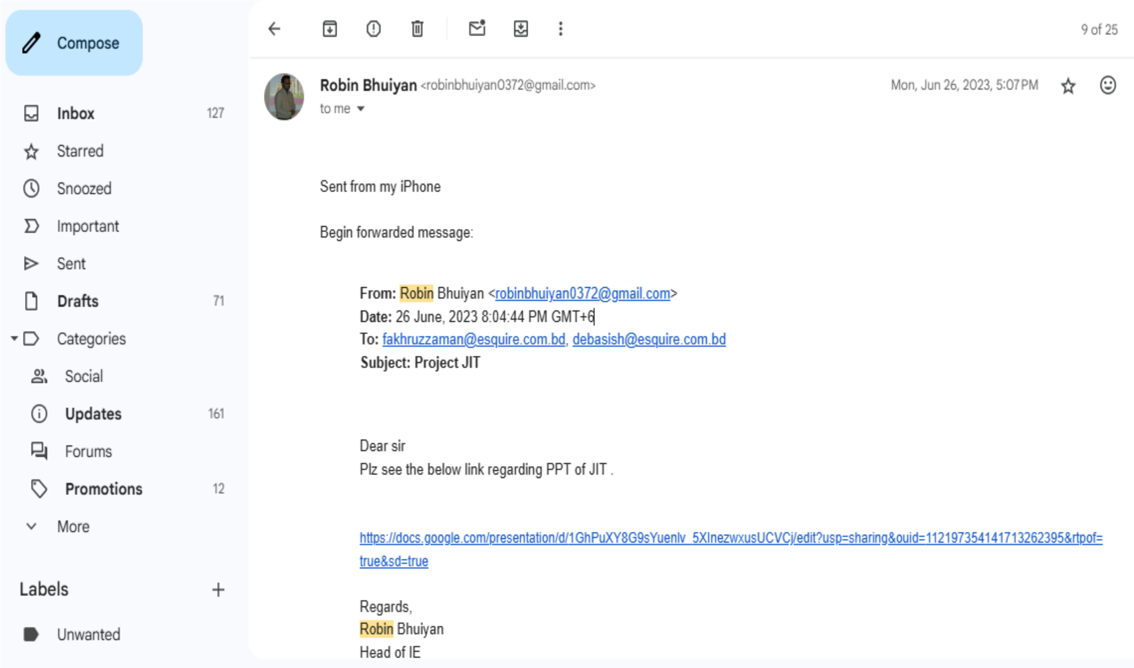


Figure 15: Data Collection for JIT