

Optimization of Socks Production in South African Knitting Plant: A Cost-Effective Alternative to Industry 4.0

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ABSTRACT

The textile industry, particularly sock manufacturing, faces increasing demands for productivity and cost efficiency amid global competition. This study presents a comprehensive case study on optimizing sock production in a South African knitting plant as a cost-effective alternative to Industry 4.0 adoption. The Research aims to identify and address key factors contributing to low productivity by employing a data-driven approach integrating Six Sigma methodologies and simulation analysis. Production data revealed that frequent system failures caused significant stoppages, material waste, and reduced operational efficiency, with approximately 8% of production output lost to defective socks. Detailed analysis using Failure Mode and Effect Analysis (FMEA) and a cause-and-effect diagram identified machine- and material-related issues as the primary contributors to poor performance. A planned maintenance strategy was developed based on the Mean Time to Failure (MTTF) of major equipment, and its impact was simulated using Any Logic software. Simulation results demonstrated that implementing scheduled maintenance, reducing failure rates by 50%, could increase system availability to 91% and substantially decrease fabric waste. The novelty of this study lies in demonstrating an effective optimization strategy that avoids the high cost and implementation barriers of full Industry 4.0 integration while achieving comparable productivity gains. This simulation-based maintenance framework provides a practical, data-supported solution for enhancing efficiency, reliability, and competitiveness in conventional manufacturing systems. The findings suggest that similar textile plants can adopt this approach to achieve sustainable production improvements without undergoing complete digital transformation.

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1. Introduction

The Manufacturing industries play a crucial role in the economic wealth and growth of a nation. In South Africa, agriculture had contributed around 2.57 percent to the GDP, whereas industry and services had contributed 24.44 and 62.61 percent of the total value added, respectively in 2022 (O'Neill, 2022). This indicates that besides the service rendering companies, manufacturing industries contribute significantly to the economy in South Africa. The textile industry, including the production of socks, plays a significant role in the global economy. The production of socks is a significant aspect of the textile industry, catering to the global demand for comfortable and fashionable footwear.

Besides the rising demand due to the increase in fashionable footwear, another factor that increases the demand is the season, which is driven by changing climatic conditions. This has also introduced diverse products with the aim of combating different extreme weather conditions with the comfort of the users in mind. Recently, each season has come to its peculiar changes ranging from extreme heat and heat waves during the summer season, to increased humidity in fall, and low atmospheric temperature during winter when compared to previous years (Engdaw et al., 2022). As a result, many of the textile industries in South Africa are responding to changing demands in products and the growing need for expansion to meet the expanding markets. As the popularity of stocks continues to grow, manufacturers face the challenge of meeting market demands efficiently while maintaining high-quality standards and optimizing production processes.

Other challenges facing this manufacturing sector are the government policies on trade liberalization and change management within the industry. While the former factor is external and out of the control of management, the latter factor is responded to by the management to optimize productivity. Introducing Industry 4.0 technologies as an optimization strategy within the manufacturing systems could be a potential solution to a few challenges affecting the knitting production plant. Smart manufacturing, using industry 4.0 technologies, integrates machines, information systems, products and people throughout the entire manufacturing process (Waibel et al., 2017). According to Olalere & Olanrewaju (2020), smart manufacturing systems, enabled with industry 4.0 technologies, consider product monitoring and assessment, machine health and operating parameters monitoring, as important factors for intelligent decision-making on a production line through the developed cyber twin of the machine tool for production optimization. Caballero-Morales et al., (2023) envisioned and proposed the implementation procedure of Industry 4.0 technologies in both the fabric production plant and well as the knitting plant, driven by the products, customers, and enterprise need. This technological advancement however has its own challenges which may be a downside to implanting this on the knitting plant.

The influence and economic power of South African textile industries and retailers together account for 90% of the South African apparel market and have an increasing retail presence across the subcontinent (Pasquali et al., 2021). The industry imports a large quota of its textile raw materials from its neighboring countries, Eswatini and Lesotho, and produces an apparels and textile products across southern African countries, making this industry an integral part of South African manufacturing industry. The challenges faced with this industry do not only impact the manufacturing sector of South Africa but also affect the textile market supplies within the southern African region. A study by Pradhan & Agwa-Ejon (2018), many manufacturing industries in South Africa are struggling to survive due to the challenges in adopting Industry 4.0 technologies which is seen as a way of addressing many of the internal operational challenges it is facing. This could be traced to factors such as the high cost of transforming existing facilities into smart manufacturing systems and the upskilling cost of the workforce. Many of the existing manufacturing industries have had to optimize their production system, and operations to stay above board with competing with the new emerging smart manufacturing industries. This involves efficiently managing the internal factors within their control to maximize productivity and operations and compete with other smart industries. The challenges of transitioning into industrial 4.0 technologies have therefore made the investigation of a possible optimization strategies for the knitting plant essential to the survival of these industries.

This study therefore investigates the strategies for optimizing production in a knitting textile industry, in South Africa, without upgrading to smart manufacturing with the potential for Industry 4.0 and digital technology integration for improvement in operation. The study explores the internal factors within the management's control and investigates an effective solution for optimizing production while running the current operational technology. Each possible opportunity for improvement within the internal factors is explored for improved productivity. A detailed analytical approach was adopted considering both qualitative and quantitative analysis followed by detailed evaluation using a simulation approach. The primary data from the production facility as well as the enterprise resource planning system is utilized for the study and both quantitative and nonquantitative statistical quality control (SQC) tools, six-sigma methodology, and simulations. The study explores a

socks production factory as a case study, with a robust system that employs a similar production system similar to other textile industry. This means that this research approach used can be applied to other sectors of the textile industry, as they follow comparable production processes.

Some challenges of adopting Industry 4.0 technologies by many South African manufacturing industries and SMMEs are the lack of expertise/skills to comprehend the complexity of smart manufacturing and the lack of financial and human resources to implement smart manufacturing (Gumbi & Twinomurinzi, 2020). The integration of 4IR technologies such as the Industrial Internet of Things (IIoT), smart sensors, cyber-physical systems (CPS), artificial intelligence, intelligent ERP systems, etc., into the conventional manufacturing system has the potential to change the trajectory of production and the overall output. According to Plessis & Marnewick (2017) intelligent manufacturing, using industry 4.0 technologies, is capable of overcoming some challenges inhibiting growth and productivity in the manufacturing industries in South Africa. Even though smart manufacturing system can address some challenges facing productivity, development, and internal management problems, it is not without some challenges associated with adoption and implementation of factories in South Africa. According to the study by Kumar (2021), some fundamental challenges with transitioning existing manufacturing system to smart industries are; disruption of labour and reliability, affordability of technology, income disparity, lack of standard regulations, issues with change management, etc. Even though research survey conducted by Geissbauer et al., (2016), in over 2000 companies from 2016 shows that transitioning to digital, and smart technologies resorted to annual cost reduction and revenue increment of 3.6% and 2.9% respectively, the challenges with transitioning comprises of complex interactions and holistic understanding, social acceptance, labour upskilling, implementation cost, and security. These remained a great set-back for most traditional industries in South Africa, making it essential to investigate an alternative approach to optimize the production system.

Textile industries in South Africa are equally faced with these challenges, with the knitting plant currently being less productive in terms of performance and output from the production facility. It becomes a challenge to optimize production within a South African socks manufacturing company that still operates under a conventional production system. The research question is therefore highlighted: What are the strategies for optimizing productivity in the knitting plant of a South African socks manufacturer without transitioning into smart manufacturing using Industry 4.0 technologies? While challenges associated with transitioning to Industry 4.0 technologies have hindered the company from moving from conventional to smart production, it becomes imperative to explore alternative methods to optimize the existing system for improved productivity. This study seeks to identify an optimal approach for enhancing production efficiency within the knitting plant by considering several controllable factors under management supervision and addressing challenges related to adopting Industry 4.0 technologies. This approach becomes essential for ensuring the survival of conventional textile manufacturing industries in South Africa in an increasingly competitive and fast-evolving economic environment.

The case study focuses on one of the largest specialty sock producers in Southern Africa, which manufactures fashion, technical, sport, workwear, and industrial socks. Fig. 1 illustrates the knitting production floor, highlighting the extensive scale of the facility. With approximately 70 years of continuous operation, the company has established itself as one of the region's oldest and most trusted brands for health-conscious consumers. Despite its long-standing experience and strong market presence, the organization, similar to many others in the sector, is experiencing a decline in sock production within its knitting plant, which affects its competitiveness amid growing market demands and advancing technologies. Several challenges are associated with upgrading its existing knitting facilities to smart manufacturing through Industry 4.0 technologies, which could potentially enhance productivity.

Change management, affordability of technology, disruptions of labor amongst others are few factors limiting the transition to smart manufacturing through adopting industry 4.0 technologies. The company therefore seeks other strategies to optimize its production facility and stay competitive while still operating its current manufacturing system.



Fig. 1. Knitting Plant Layout. The production floor of the knitting facility, showing the extensive size and operational capacity of the manufacturing area.

2. Method

The study explores the current state of the knitting plant production lines, and its previous production data to uncover and assess the current trend of events within the production facility. The significance of this study lies in its potential to optimize sock production in a knitting plant, leading to improved operational efficiency, reduced costs, enhanced product quality, environmental sustainability, and increased market competitiveness. The study adopts a research approach that follows a theoretical concept of research onion, that consists of both qualitative and quantitative strategies (Saunders et al., 2009; Saunders & Bristow, 2023). Research philosophy, research approaches, strategy, choices, time horizon, processes, and data-gathering methods are the fundamental layers of research onion. The quantitative approach analysis the current and historical production data using some quality tools and techniques to quantify the trend in the manufacturing KPIs.

This approach was adopted by Rojas et al., (2024), using quantitative modelling approach for lean manufacturing for the optimization and simulation of production outlay. Applying this approach on the areas and sectors of the production will uncover the gap within the production process with the possibility of improvement strategies. This entails adopting some quantitative data analytics tools, such as Failure Mode and Effect Analysis (FMEA) and Causes and Effect diagram, on the current production data to uncover the challenges and the shortfall in the current production. While the former tool examines the current production system and identifies the failures and challenges, and how each failure occurs in the system, the later tool explicitly enumerates the causes of a major effect under consideration under six main possible potential causes. For example, a quantitative analysis of a conceptual system dynamics maintenance performance was adopted for optimizing the production through support for decision-making (Linnéusson et al., 2018). The action strategies adopted in the study were able to optimize the production system through support for maintenance decisions on the production machines. Similarly, Sahu & Pradhan (2016) applied quantitative analysis in the optimization of production with the focus on line-balancing using discrete event simulation techniques.

This study therefore applies quantitative analysis and simulation techniques to the identified internal operations within the company. This includes application of relevant tools and techniques in identifying the operations that require review and upscaling while applying simulations techniques in evaluating the augmented reality of the procedures and application of the proposed strategies. Since the study focusses on critical production data, and do not involve human participants, ethical clearance is not required for the research implantation, however, a verbal consent was taken from each participant in connection with the production data acquired from the factory plant.

2.1. Research Framework

This is a conceptual structure, which provides a simple and systematic approach to solving research problems. This section presents the study overview and the systematic approach followed in performing the study. According to Souza & Alves (2018), implementing optimization strategies in a production system requires auditing every sections of the manufacturing system, analyzing the system, proposing and implementing improvement strategies using diverse methodologies such as lean, machine maintenance strategies and evaluating the solutions. A similar approach was adopted by Svensson & Paramonova (2017), but focused on the energy efficiency improvement of the production system. Recent studies have integrated industry 4.0 requirements in optimizing manufacturing systems, Jaskó et al., (2020); Motzer et al., (2020), however approaches optimizing the production system exclusive of Industry 4.0, smart manufacturing technology. The framework starts with identifying the requirements that affect the production of sock, knitting machine and quality of yarn, followed by conducting a detail process appraisal through data collection and analysis, then developing the optimization strategy, followed by the implementation and evaluation, and lastly conducting the impact assessment as illustrated in Fig. 2. The overall aim of the framework is to identify the challenges with the current production system and examine an optimized strategies for improvement without adopting industry 4.0 technologies.

The collection of relevant data regarding the current production process, including production rates, cycle times, material usage, machine capabilities, and Laboure were considered for data analysis. The data analysis approach and optimization strategy incorporate lean six-sigma methodologies, DMAIC, and quality tools and techniques in reviewing and developing improvement plans, while the implementation and evaluation stage applies simulation strategies using discrete event simulation (DES). The methodology focuses on improving the textile knitting process and products, using a structured data-driven approach with the first stage being to define the problem or opportunities for improvement, followed by the measurements of the system parameters, and the analyses of the gathered data to identify the root causes of the problems.

Determining the root causes of the problems encountered by the manufacturing plant is highly essential for the study as it determines the approach and solutions deployed to solving the problem. At this phase, several tools are used for determining the root causes of the problems and to ensure that it is right problem is addressed with corresponding order of importance. A very important tool used is the FMEA tool that examines each failure in the system and evaluates how each failure occurs, to determine the solution. As seen Fig. 4, the last two steps of the strategy of the DMAIC strategy are the improvement of the system by implementing the proposed solution and the monitoring and control of the implemented solutions. The strategy directly aligns with the research onion stages with the core inner stage of the onion being the data collection and analysis, while the research strategy of the onion adopts an archival data collection and simulation analysis. The third layer of the research onion is the methodological choices which is linked to the mixed method adopted at the data analysis phase of the research framework. Some qualitative and quantitative tools were used to analysis the current condition of the knitting plant with the aim of unraveling the challenges and problems faced during socks production.

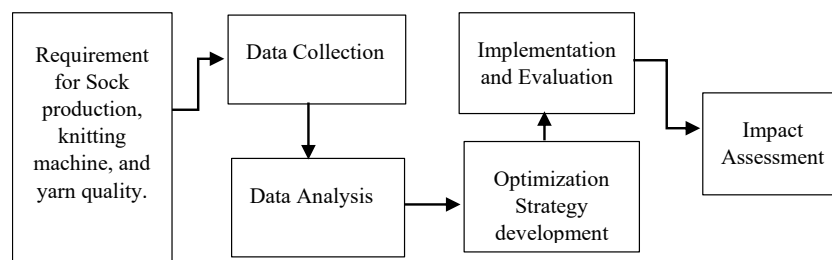


Fig. 2. Research Framework. The overall aim of the framework is to identify the challenges with the current production system and examine an optimized strategies for improvement without adopting industry 4.0 technologies.

2.2. Research Data Collection and Process Approach

This describes the knitting plant process and the research approach adopted in the study. The study approach evaluates the operations, machines, and production data at each stage of the manufacturing process lean six sigma, DMAIC strategy. The manufacturing of Sock in the industry covers seven main operation stages of the manufacturing process as illustrated in Fig. 3. This begins with the yarn preparation, through till the dispatch stage of the manufacturing process, ensuring that every possible challenge within the system is identified and opportunity for improvement is considered. The research approach applies the principles and tools of six sigma to DMAIC (Define, Measure, Analyze, Improve and Control) framework to evaluate and address the quality related challenges in the knitting plant factory. The first step of the process clearly identifies and defines the problems associated with the entire production system. According to a study by Olalere & Ramdass (2024), Overall Equipment Efficiency (OEE) is an effective performance metrics for evaluating the performance of any manufacturing system with a focus on driving improvement initiatives. This manufacturing KPI covers the main core aspect of a manufacturing industry that indicates the performance level of the industry and at the same time identifies improvement areas of the system.

The study therefore considers the quality of the product from the system, performance data as well as the equipment availability during production. The measurement phase examines the process through collection of key performance data from the entire production system and measuring the defects, and anomalies with the current production system.

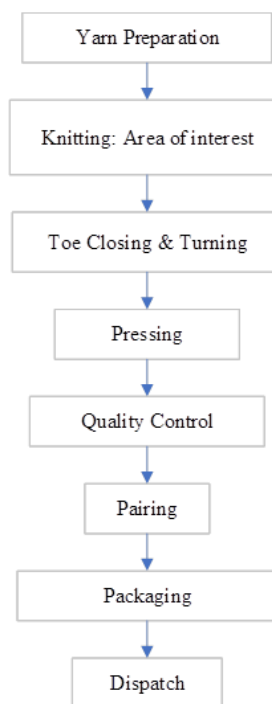


Fig. 3. Production Process Flow Chart. The manufacturing of Sock in the industry covers seven main operation stages of the manufacturing process

The study approaches the analysis phase through a data-driven approach by critically reviewing the production data, identifying the process improvement opportunities, and improving the process flow. This approach as compared to Industry 4.0/ smart manufacturing strategies seeks to optimize production through eliminating inefficient workflows, redundant tasks, non-billable activities, quality improvement plans through data-driven approach as against industry 4.0 technological interventions. Improvement and optimization strategies could entail changes in material selection, adjustment in production methods, equipment, or machineries maintenance. The control phase evaluates the significance of the proposed implemented solution using a simulation approach as compared with

overhauling the entire production facility to smart manufacturing systems. The simulation approach evaluates the system parameters using the MTTF of each major failure encountered during the knitting process and the MTTR of each of these failures. It then simulates the operation system to determine the availability of the system, considering the run time, the possible downtime, and the number of scheduled maintenances to be carried out within a considered period. The outcome of the simulation would project the significance of the proposed approach in reducing the overall downtime, the number of scraps and rework and possible cost benefits as compared to implementing the industry 4.0 technologies and its challenges. The simulation result would examine the MTTF of the challenges experienced during the manufacturing process causing production downtime, evaluates the possible downtime when scheduled maintenance is adopted and correspond it initial state. This validates whether the solution is feasible or not.

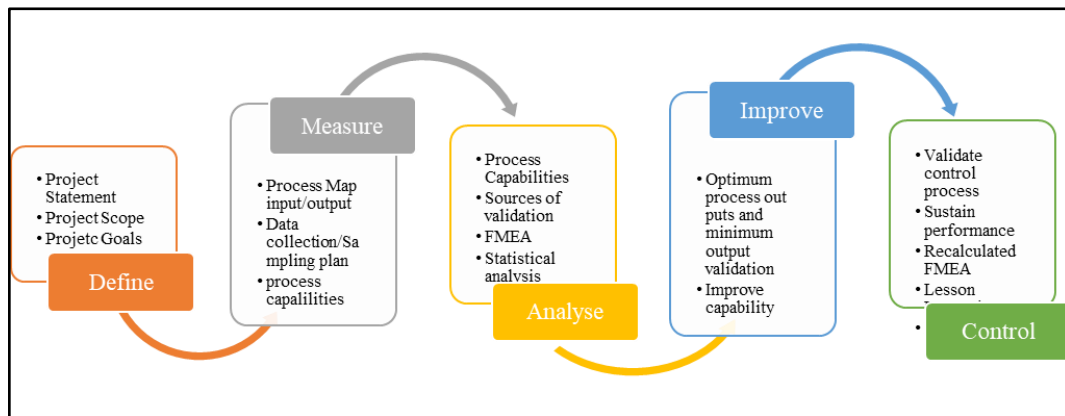


Fig. 4. DMAIC Research Approach

A deductive reasoning approach that draws inferences from the data analysis based on existing theories and laws were also adopted in the analysis in projecting solutions for improvement strategies. The structured approach aims at identifying and resolving issues, improving processes, and achieving better performance and quality outcomes. The FMEA tool is considered for analysis of the equipment, its availability and the effectiveness of the maintenance procedure adopted by the system. According to [Rajapaksha et al., \(2015\)](#), FMEA is good at exhaustively cataloguing initiating faults and identifying their local effects. The study evaluates the entirety of the production system through evasive consideration of the factors which are functions of OEE. as indicated in [Eq. \(1\)](#).

$$OEE = \text{Availability} * \text{Quality} * \text{Performance} \quad (1)$$

The equipment performance factor measured through the availability factor of OEE delineate instances of operational imbalances, specifically, the contrasting dynamics between run-full and run-short conditions resulting from bottlenecks attributed to machine operating condition, and material and product quality.

2.3. Simulation Approach

Any Logic simulation software is deployed in developing a model that evaluates the discrete event of the number of failures of each failure type when a planned maintenance approach is adopted. The production data archive from the knitting plant is analyzed to determine the challenges, the MTTF and MTTR of these challenges are used for the simulation analyses. The MTTF and MTTR data is used to simulate the planned maintenance strategy which is divided into two maintenance scenarios. The first scenario uses the MTTF to simulate the planned maintenance and determine the system downtime for a scheduled maintenance. The schedule maintenance interval is determined by the failure rate of the top failures experienced by the system. The first scenario assumes that the planned/scheduled maintenance reduced the failure rate by half, and the second scenario considers a

fixed hourly interval of maintenance based on the failure with the lowest MTTF. The overall availability of the system is determined to evaluate the significance of the approach in optimizing the knitting plant.

3. Results and Discussion

An observation of two knitting production lines producing low cut sock was carried out to investigate different failures that occur during production time. The knitting machines were observed for 120 minutes during the operation and two notable types of stoppages were recorded during the operation as indicated in Table 1. The low cut sock type production is observed during the 120 minutes of operation, with an average cycle time of 2 minutes. The frequency of occurrence of each type of failure causing production downtime, the downtime, and the total downtime for each failure type was also recorded as shown in Table 1.

Table 1. Data Collected Through Observation

Stoppage	Frequency (Time in seconds)	Total Downtime	Total Production Time
Breaking Yarn	165 201 83 172 41	621	
Breaking Elastic	151 71 -- -- --	734	
copy	0	1355	7200

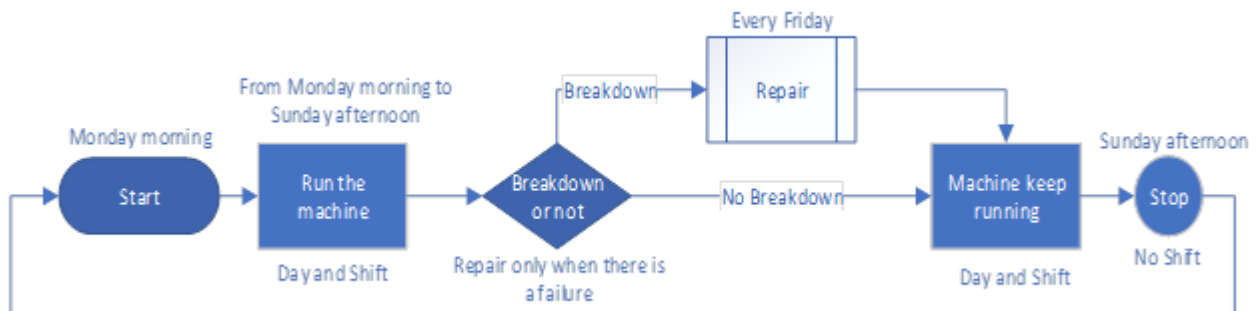


Fig. 5. The Current Maintenance Policy Framework

The observation of the production gives an idea of some challenges that are encountered during production. This commenced by reviewing the current knitting plant production schedule and data for a week as indicated in Fig. 5. As illustrated in Fig. 5, a breakdown maintenance policy that runs the machine concurrently till any failure occurs before repair or maintenance is carried out. Unlike preventive maintenance, this maintenance policy according to Erbiyik (2022) is preferable as special equipment is not required, maintenance manpower size is small, technical competence of manpower required low, and computer back-up is not necessary.

It is therefore reasonable for the maintenance system to adopt a breakdown maintenance policy based on the conditions of the manufacturing system. The manufacturing KPI for the observed production time of 2 hours is calculated by determining the OEE. OEE considers the key factors during the manufacturing process which are the machine/equipment availability, the performance of the operator and the quality of the product being produced. In addition, the planned production, actual production, lost production is determined within the observed production time.

$$\text{Uptime} = 7200 - 1355 = 5845 \text{ sec}$$

$$\text{Planned production} = 7200 / (2(60)) = 60 \text{ socks}$$

$$\text{Actual production} = 5845 / (2(60)) = 48.7 \approx 48 \text{ socks}$$

$$\text{lost production} = 60 - 48 = 12 \text{ socks}$$

$$\text{Availability} = (\text{Planned production} - \text{Actual}) / (\text{Actual Production})$$

$$\text{Availability} = 75\%$$

During the observed production time of 120 minutes, the two machines producing a low cut sock with an average cycle time each had lost production of 12 socks due to machine downtime due to stoppages based on production glitches such as braking yarn and elastic. To further understand and analyze the production trend and operation, the previous production sheet for 20 days is considered.

Table 2. Production Data for 20 Days

Stoppage	Frequency	Average Downtime Per failure (min)
Breaking Needles	143	2.5
Electronics	51	10
Breaking Spandex	165	3.0
Oil Pressure	7	1.0
Breaking Elastic	135	4.1
Water inside	4	3.5
Breaking Yarn	97	2.5
Platting	29	2.5
Knife	19	1.5
Breaking Cam	9	15
Breaking Sinkers	7	1.5
Breaking Heel & Toe	21	2.5
Couleur Changer	11	1.5

Table 2 shows the data of the breakdowns experienced over a period of 20 days, comprising of the failure as well as the frequency of occurrence and the average downtime per failure. The production data shows 13 different failure types over a period of 20 days, with varying frequencies of occurrences. To understand the failures in order of frequency of occurrence, the data is illustrated in Pareto chart, ranging the failures from the highest of occurrence to the lowest as illustrated in Fig. 5. The chart indicates breaking spandex is the highest occurring failure while the least failure was water inside. To understand the impact of each failure type, it is good to consider the average downtime of each failure.

This can be explained as the time it takes to restore the system to normal each time the failure occurs. This would help with investigating the impact of each failure and its frequency during production. The total downtime is derived from the product of the average downtime per failure multiplied by the frequency of each type of failure. This data indicates the impact of the failure type on the loss in production time, hence the problem that should garner more attention. The Pareto chart of the downtime per failure type is also plotted to show the range of the failure with the highest loss in production time to the lowest.

Fig. 6 shows the impact of each breakdown type on the operations and the frequency of each of the breakdown types. This indicates that breaking elastic has more impact on the operations of the system than any other failure types. The first six (6) failures in Fig. 6 can be further investigated and the approach to reduce these failure occurrences can be implemented. According to the study by (Wu et al., 2021), Failure Mode and Effect Analysis (FMEA) play a better-quality control role in complex manufacturing products or systems in identifying the root-cause of quality defects or production failures in a system.

According to Olalere & Ramdass (2024) applied FMEA tool and Cause and Effect diagram in analyzing the production defectiveness and troubleshooting the challenges with achieving the First-Time Capacity (FTC) of the production target in an automobile plant. Similarly, both the FMEA and Causes-and-Effect diagram is used to analyze the root causes of the top five highlighted failures with highest impact based on the downtime on the production system.

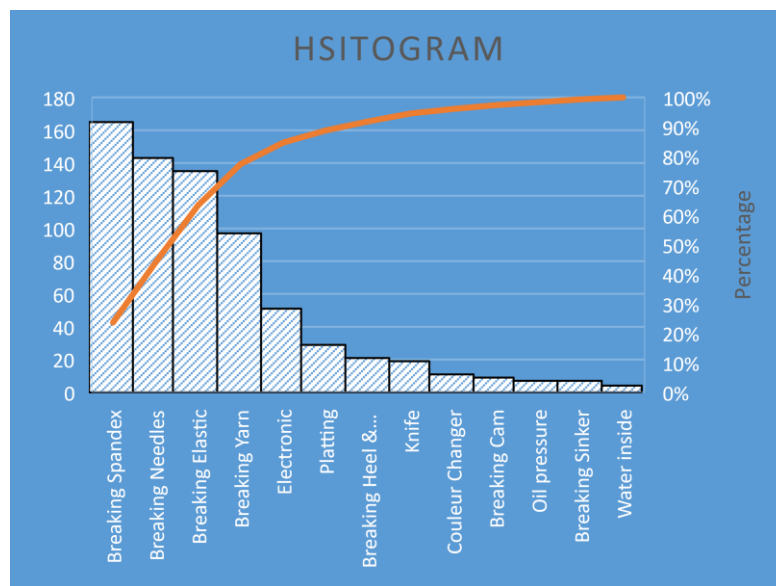


Fig. 6. Pareto Chart of Failure Occurrence

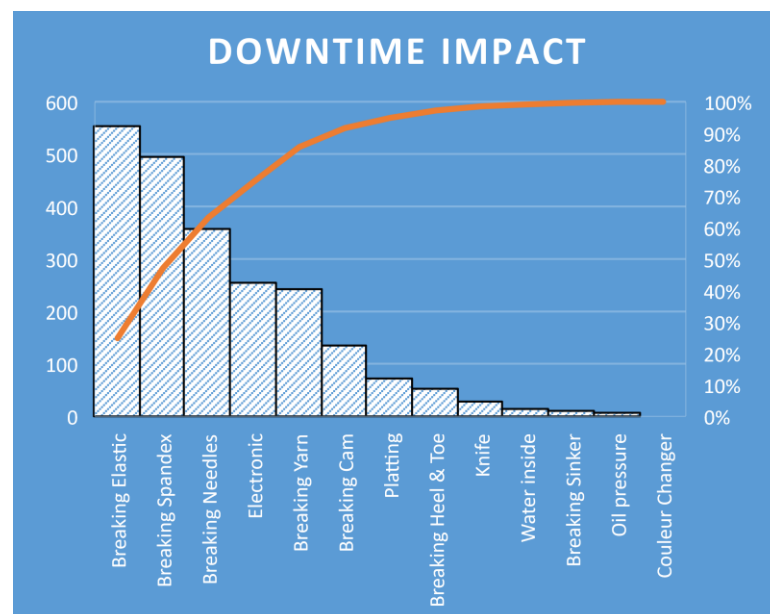


Fig. 7. The Pareto Chart of Downtime and Causes

3.1. Root-Cause Analysis of Knitting Plant Failures

To optimize the knitting manufacturing plant, the top 5 failures with the most impact on the downtime of the machines is considered in this study. The approach follows a systematic problem-solving technique in identifying the fundamental reason(s) why a failure occurred, using both the causes-and-effect diagram and FMEA analysis. The causes-and-effect diagram, also known as Ishikawa or Fishbone diagram unravels the likely possible causes of a failure effect in a production process. The causes of top six failures namely, breaking elastic, breaking Spandex, electronics, breaking needle, breaking yarn, and breaking cam are highlighted on the left side of the causes-and-effect diagram as indicated on Fig. 7. These possible causes are further disintegrated to understand the root causes of the problems and how they are interrelated. A study by Pamungkas & Iskandar (2022) applied the integration of FMECA and Fishbone analysis for analyzing defects for quality

improvement in a boat manufacturing process, and the outcome revealed several factors affecting the production lines which if addressed could increase the productivity of the process without much capital investment. This study therefore hopes to optimize the production of the current knitting manufacturing plant, as against investing capital in the industry 4.0 technologies transformation of the existing infrastructure.

The quality of the raw material can be associated with three production failures of the top five failures causing downtimes in the system from the Fishbone analysis in Fig. 8. It is worthy to also consider the life-history phase of the machine when examining the reasons for machine failure and maintenance adopted. While the chance failure phase in the life history curve of the production plants might offer the highest machine efficiency state [Han et al., \(2021\)](#), the maintenance policy adopted could be leveraged in optimizing the current production efficiency and output. The failure mode and causes of the top six failures with highest impact on the production efficiency is highlighted in [Table 1](#). The FMEA analysis revealed that the cause of four failures during the production system are closely related to each other. The corresponding trigger event causing the failures are the same, and this implies that a concerted effort to address any of these four failures would address the other three. Breaking yarn, breaking spandex, breaking elastics, and breaking needle are mainly caused by the same trigger actions. The solution is therefore implemented to address these four failures to optimize production efficiency. The causes of the electronic as well as the breaking cam failure are also identified, and the mode of failure as presented in [Table 3](#).

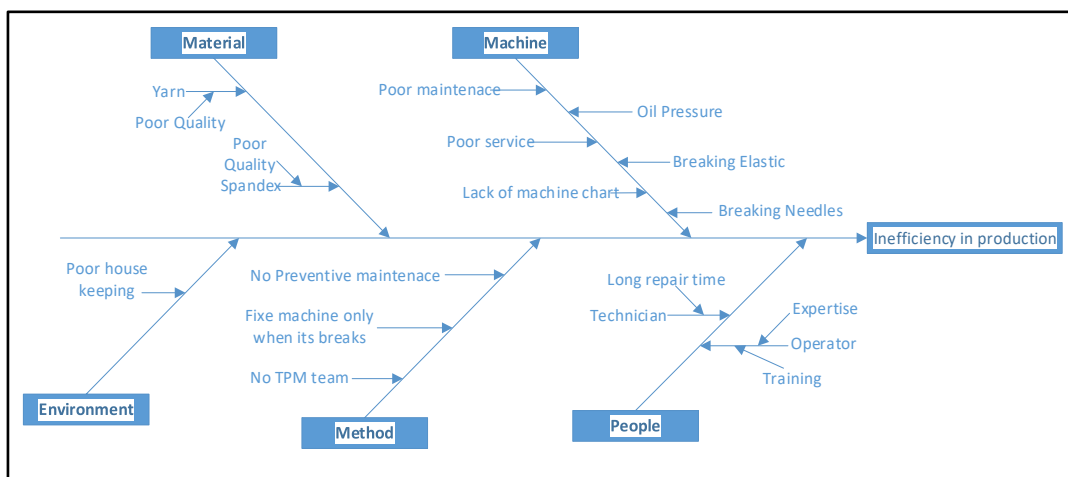


Fig. 8. Causes and Effect Diagram for Root Cause of Production Inefficiencies

The FMEA analysis also indicates that the current manufacturing plant is prone to breakdown maintenance issues, hence, the maintenance approach could considerably offer a solution in the production optimization effort in the system. A similar study by [Quiroz-Flores & Vega-Alvites \(2022\)](#), adopted a revised maintenance approach in optimizing the production efficiency of a plastic manufacturing plant with the result yielding an increased production output. While breakdown maintenance could be productive at an early phase of a machine, planned maintenance is preferable almost at the end of the useful life of the machine. This study therefore considers the potential for optimizing the production efficiency from the maintenance policy currently adopted. The proposed solution is reviewed based on the current operations and policy and the analyzed data, as against implementing a smart manufacturing system, through smart system argumentation.

3.2. Proposed Solution for Production Optimization

The aim of the optimization effort is to increase the production efficiency through reducing the downtime of the production plant, reducing the number of scraps, and improving the quality of the products manufactured as an alternative to implementing industry 4.0 technologies due to its challenges. The production data for a week shows that the production target was 155804 products, but

the production achieved was 133584 with 13542 number of scraps/reworks. This shows that the production efficiency was 77% with an 8% loss in efficiency during the production week considered. The production data is illustrated in Fig. 3.

Repair and preventive maintenance measures such as, lubricating the CAM and replacing the faulty electronic components are adopted at scheduled maintenance interval using the Mean Time to Failure (MTTF). MTTF is the average time it takes a component or a system to operate or perform its intended function satisfactorily before it breaks down. It evaluates the average time between each successive breakdowns to determine the average time between repairs. The 20 days production data in Table 2 is used to calculate the Mean Time to Failure and Repair (MTTF and MTTR) for the top six failures considered in order to determine the maintenance that is best for the current system with the aim of optimizing the production. The formular for evaluating the MTTF and MTTR is stated in Eq. (1) and Eq. (2) respectively.

Failures	Actions/Solutions
Breaking Elastic	Improved Quality of Yarns/Spandex/Elastic Inspection of needle for operational mis-match Fixing connecting jack Preventive maintenance (re-setting tensions)
Breaking Yarn	
Breaking Spandex	
Breaking Needle	

Fig. 9. Proposed Solutions for System Failure

Table 3. FMEA of the Top Six Failures

FMEA System Element	Function	Failure	Failure Effect	Cause
Re-setting and continuing the production	Production of fabrics and items with elastics.	Breaking Elastic	Downtime due to discontinuation of operation.	Worn connecting jack, low quality elastic,
Re-setting the spandex, discarding scraps, & continuing production	Production of fabrics and items with elastics.	Breaking Spandex	Downtime due to re-setting.	Low quality of yarn, tension of the yarn, Worn connecting jack, Mis-match needles,
Technical fixing of the electronics part of the machine	Controls and operation of machines	Electronics	Downtime due to machine stoppage.	Lack of preventive maintenance
Twisting the yarns and spandex to form fabrics	Knitting and twisting the yarns and spandex	Breaking Needles	Production stoppage.	Worn connecting jack, Jack linking is not needling Centre (settings modified)
Re-setting the yarn, discarding scraps and continuing production	Manufacturing of fabrics	Breaking Yarn	Downtime due to Re-setting.	Low quality of yarn, tension of the yarn, Worn connecting jack, Mis-match needles,
Driving the follower for operating the machine	Production of fabrics and items with elastics	Breaking Cam	The ability to operate is impaired.	Cam non-lubrication,

$$MTTF = \frac{\text{Total Operating Time}}{\text{No of failures}} \quad (2)$$

$$MTTF = \frac{\text{Total Maintenance Time}}{\text{No of Repairs}} \quad (3)$$

$$\text{Efficiency} = 1 - \frac{\text{Total failure}}{\text{work rate}} * 100 \quad (4)$$

Table 4. Top 6 Failure's MTTR and MTTF

Stoppage	Frequency	Average Downtime Per failure	MTTF	MTTR
Breaking Needles	143	2.5	2.23	2.5
Electronics	51	15	6.23	15
Breaking Spandex	165	3.0	1.94	3.0
Breaking Elastic	135	4.1	2.37	4.1
Breaking Yarn	97	2.5	3.30	2.5
Breaking Cam	9	15	35.56	15

The data in Table 4 shows the MTTF and MTTR which are considered in determining the interval of routine reset and maintenance on the plant during the production process to lower the chances of failure by adopting the planned preventive approach. Since the least MTTF is approximately 2 hours, the machine reset of the connecting jack is done every 2 hours to reduce the chances of failure. This automatically would reduce the chances of the four failure types highlighted in Fig. 8, since they have a common root cause. A set time of 5 minutes is proposed for performing planned maintenance approach on the 4 failures with similar root cause. The planned maintenance for the electronics is proposed after every shift, while the planned maintenance for the CAM is proposed for every 2 production days based on the MTTF. The proposed planned maintenance reduces the chances of failure occurrence in-between planned scheduled maintenance and ultimately the number of failures for a given production hours. For a given failure type with 2 hours MTTF, it means there is an 100% chance of a failure in 2 hours. Therefore, for a given failure within hours of production, the failure rate can be evaluated using Eq. (4).

$$Fr_{(y \text{ hours})} = \frac{\text{Total no of Failure}}{y \text{ hrs of Production}} \quad (5)$$

From expression, the failure rate of each type of failure can derived as indicated in Table 6. The data in Table 5 and Eq. (5) also shows that three failure types also have approximately the same MTTF, which means that scheduling a planned maintenance within this time could potentially inhibit breakdown or failure within the production system. The planned maintenance of the knitting machine, which mainly consists of re-setting and routine maintenance could therefore be scheduled for every 2 hours.

Table 5. Failures and Probability of Occurrence in 2hours

Failures	MTTF	Fr_{2hrs}
Breaking Needles	2.23	0.447
Electronics	6.23	0.159
Breaking Spandex	1.94	0.516
Breaking Elastic	2.37	0.422
Breaking Yarn	3.30	0.303
Breaking Cam	35.56	0.028

The data in Table 6 is used in simulating the occurrence of each failure type in-between the planned maintenance based on the analysis and the results of the top major challenges. Any Logic simulation software is used to determine the number of likely failures, the time spent on planned maintenance during the production time considered and the overall efficiency of this approach in optimizing production.

3.3. Simulation of the Optimization Approach Using Anylogic

The first routine maintenance involves resetting of the knitting plant, adjusting the tensions of the Yarns, elastics, spandex, re-setting the jack and inspecting the needles, while the second maintenance routines involve checking the electronics and lubricating the machine CAM for preventive maintenance. While the first routine maintenance is scheduled for every 2 hours, which is based on the probability of the most occurring failure derived from the MTTF. The second planned routine maintenance is scheduled for every 8 hours production shift, which considers the routine maintenance of the electronic components and the lubrication of the CAM drive of the knitting plant. This approach examines the number of failures occurrences based on the probability determined by the MTTF and the maintenance time-interval.

Scenario I. The probability of each failure occurring is programmed based on the initial failure rate obtained from the production data as highlighted in Table 5. The first scenario assumes that the planned/scheduled maintenance reduced the failure rate by half, since the maintenance and resetting of the machine is done just before the average MTTF of the top five failures. Each failure occurrence in the production floor is indicated through an agent moving into the storage for each failure type. Each routine maintenance done after 2 hours, and 8 hours of production is also indicated through an agent moving into the respective storage as indicated in Fig. 9.

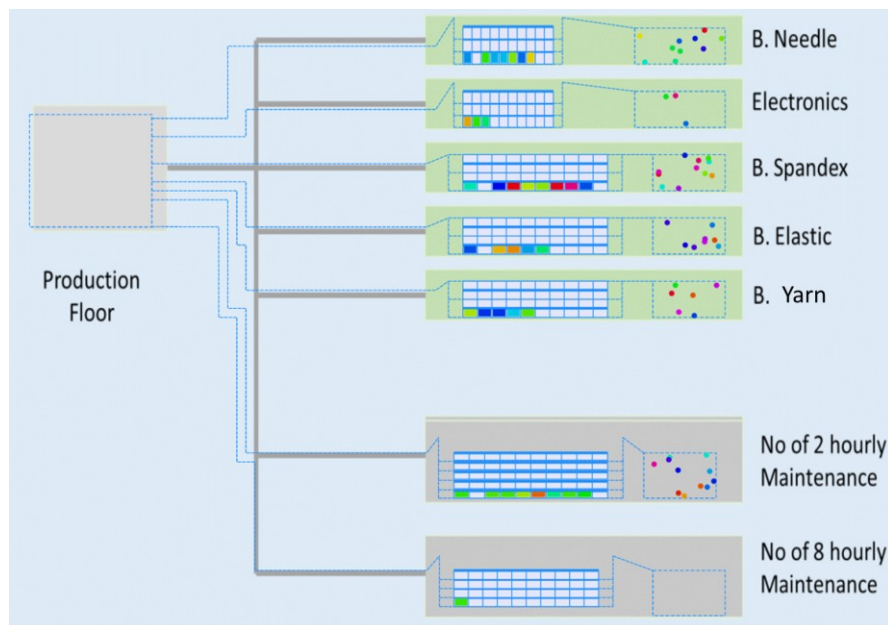


Fig. 10. Simulation of Knitting Production Plant Failures

The model block is shown in Fig. 10 and Fig. 11, illustrating the construct of the simulation of the knitting plant production top five failures. The data from the simulation model is presented in Table 6, with the assumption that the failure rates is reduced by half with the introduction of the planned/schedule maintenance during the manufacturing process. To determine the viability of the approach at 50% reduction in failure rate through planned maintenance, the actual production and the availability of the machine is determined.

Where the total downtime of 56 minutes is derived from Table 7, which is the sum of the total downtime for the 8-hour shift. The actual Production can be determined from the equation as;

$$\text{Actual Production} = \text{Availability} / (\text{Average Cycle Time})$$

$$\text{Actual Production} = 424/2=212 \text{ socks}$$

The loss in production as a result of the planned maintenance is;

$$\text{loss Production} = (\text{Maintenance Time}) / (\text{Average Cycle Time})$$

$$\text{Loss in Production} = 16/2 = 8 \text{ socks}$$

$$\text{Availability} = (\text{Actual Production Time}) / (\text{Planned Production Time})$$

$$\text{Availability} = 424/464 * 100 \% = 91\%$$

Table 6. Simulation Data from the Model

Failures	MTTF	F_{2hrs}	No	MTTR	Downtime	Scrap
Breaking Needles	4.46	0.223	3	2.5	7.5	Yes
Electronics	12.46	0.080	1	15	15	0
Breaking Spandex	3.92	0.258	4	3	12	Yes
Breaking Elastic	4.74	0.211	3	4.1	12.3	Yes
Breaking Yarn	6.60	0.152	2	2.5	5	Yes
Breaking Cam	71.20	0.014	0	15	0	0
2hrly			8	2.0	16	0
8 Hourly			1	15	15	0

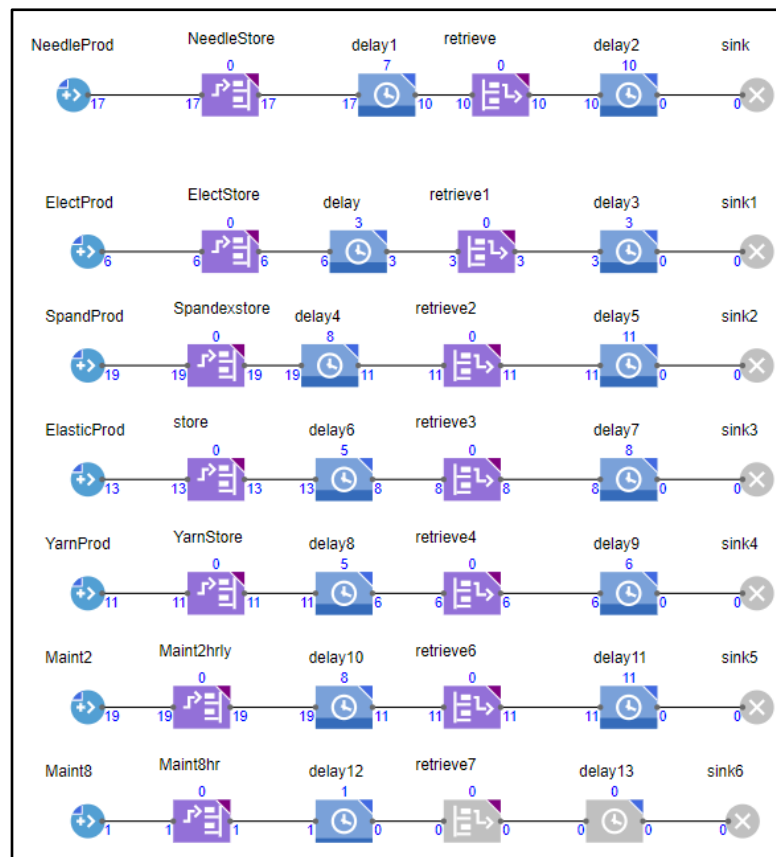


Fig. 11. Simulation Block of the Model. Availability = Total production time-Total Downtime, Availability=(8 hours*60) min-56=424minutes

The availability of the Knitting machine assuming the planned maintenance reduced the failure rate by half is 91%, while also reducing the number of scraps recorded during the Manufacturing process. Increased system availability and reduced number of scraps imply that the company becomes more competitive in the textile market and the reduction in the number of scraps means there are a lot of cost savings which boost the financial stability of the company. This outcome means that the company could compete with other companies through the optimization strategy, without having to deploy the industry 4.0 technologies with its challenges.

Scenario II. The scheduled maintenance is done after every 2hours, and the failure occur based on each failure's MTTF. Assuming that there is no failure occurring 30 minutes after the planned maintenance is carried out.

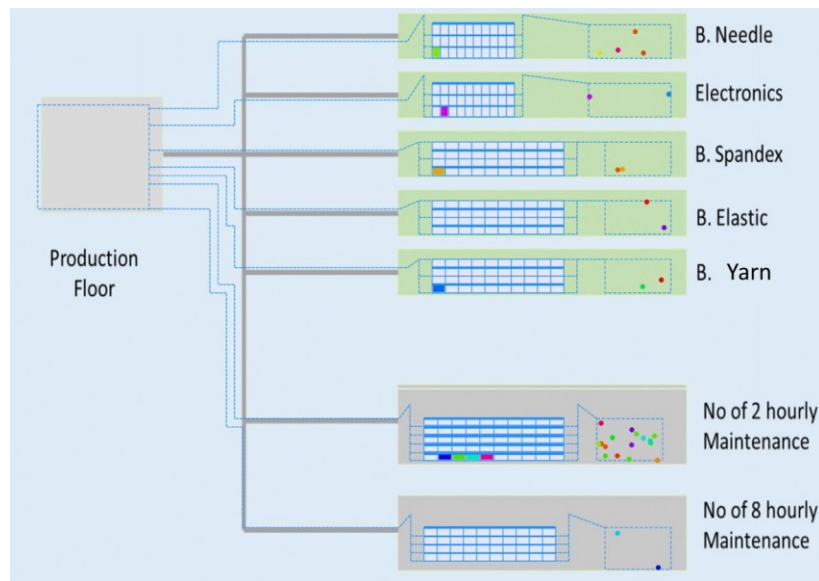


Fig. 12. Simulation for the Production Scenario II

The production simulation model after 16 hours of production time is represented as shown in Fig. 12 while the production data from the simulation model can be represented in Table 7.

Table 7. Results from the Simulation Model for Scenario II

Failures	MTTF	F_{2hrs}	No	MTTR	Downtime	Scrap
Breaking Needles	2.23	0.447	3	2.5	7.5	Yes
Electronics	6.23	0.159	2	15	30	0
Breaking Spandex	1.94	0.516	2	3	6	Yes
Breaking Elastic	2.37	0.844	2	4.1	8.2	Yes
Breaking Yarn	3.3	0.303	2	2.5	5	Yes
Breaking Cam	35.56	0.014	0	15	0	0
2hrly			16	2.0	32	0
8 Hourly			2	15	30	0

The total downtime of 83.7 minutes is derived from Table 7, which is the sum of the downtime of each failure excluding the 8 hourly maintenance which is done outside the production time. The actual production can also be calculated, as well as the loss production.

$$\text{Actual Production} = 876.3/2 = 438 \text{ socks}$$

$$\text{Loss in Production} = 32/2 = 16 \text{ socks}$$

$$\text{Availability} = 876.3/960 * 100 \% = 91.3\%$$

The availability of the production facility with scenario II is 91.3% which is within the same range with scenario I. This further indicates that adopting planned maintenance strategy which is scheduled based on the MTTF of the failure types could offer an optimized production strategy. researched into 4 knitting production lines with the efficiency of the lines [Rassel & Hoque \(2019\)](#) being 60.56%, 67%, 77%, and 79.50% with the first 2 lines being a non-air-conditioning knitting plant and the last 2 air-conditioning knitting plant. With most of the challenges similar with the manufacturing system considered in this study, the simulation result, 91.3% and 91% offers a great potential in a competing global market of textile industry. Therefore, conducting a thorough root cause analysis into the causes of failure within the production system, examining the impact of the failure to identify the significant failures and the current maintenance policy undertaken within the system are the baseline for the optimization strategy adopted in this study. Adopting a scheduled maintenance strategy thereafter reduces the number of scraps and increase the system availability by reducing the number of failures experienced. The result from the simulation with the scenario II also indicates that with an increased availability, the company can compete with other similar companies in the textile market with a reduced cost due to reduced number of scraps. The result is also an indication that the system can be optimized without necessarily adopting industry 4.0 technologies. The optimization strategy can be deployed to other industries with similar challenges with downtime from system failures with the machines at the middle to the end of their useful life.

This implies that the optimization strategy offers a more feasible solution for improving the production system at a reduced cost as compared with implementing industry 4.0 technologies which comes with some challenges. This strategy is also deployable to other industries with similar system downtime due to failures of machines and system components. This would present an alternative to the challenges and issues that comes with implementing industry 4.0 technologies.

3.4. Challenges Faced by Unreliable Equipment

Knitting plants are critical machines within the textile industry to produce fabrics, clothing, socks and reducing downtimes and scraps are essential strategies for most production managers ([Rahman et al., 2023](#)). When these machines fail, it often led to loss of production materials depending on the product design being manufactured. High rates of production defects, high scrap rates, loss of production time by knitting machine due to needle are some of the challenges that have encouraged most manufacturing industry to seek a Zero-defect manufacturing system through the adoption of Industry 4.0 and advances in digital technology ([Xu et al., 2025](#)). This new zero-defect manufacturing system is without its challenges, especially within the existing textile industry. The high cost of overhauling existing facilities and machines to the new and efficient digitalized machines, and the maintenance cost are some of the challenges facing some existing textile facilities ([Degirmenci, 2023](#)). Therefore, adopting an optimization strategy may offer a solution to increasing productivity of the existing textile manufacturing.

3.5. Applicability to other Textile Industry and Future Research

Textile industries are quite an enormous industry in Southern Africa with various products ranging from various traditional attire or products to convectional costumes. One of the challenges plaguing the textile industry is the pressure from market competition and fast changing technological innovations. It becomes challenging for the convectional industry to compete with the new ones with modern technology. Optimizing these textile industries using the proposed approach in this study could offer a reliable, cost effective and easy solution as compared to deploying industry 4.0 technologies which has some challenges attached with it.

However, the limitation of the approach is that the downtime factors must be within resolvable assignable causes and the MTTR for these failures must be within a bearable limit proportional to the failure rate. Future study could be explored on partial implementation of digital transformation in the textile industry which include condition monitoring using internet of things (IoT). Even though there might be some challenges such as technical know-how and some implementation cost which requires training of staffs and some capital investments, this can be explored as a potential solution as compared to full industry 4.0 technologies for smart manufacturing.

4. Conclusion

The research outcomes provided insights into reliability engineering strategy for optimizing knitting plant productivity, as compared to adopting Industrial 4.0 technologies to enhance the reliability engineering approach for the knitting plant. Reliability engineering practices play a pivotal role in ensuring the safety, performance, and longevity of knitting plant operations in South Africa. As the life-cycle of machines gradually move from the early-failure phase to chance-failure-phase, and lastly to wear-out phase, the maintenance approach and reliability plan becomes dynamic. The number of failures experience as the useful life of the knitting plant depletes increases, which often necessitates introducing a reliability strategy to optimize production or sustain it. Recent studies are adopting Industry 4.0 technologies to enhance fabrics productivity. These approaches may well be suited for newly installed and manufactured textile plants and machineries, with presumably high cost of maintenance and implementation. However, incorporating Industry 4.0 strategy into an old infrastructure would come with some challenges such as high cost of implementation, skill, and labor transition/change, change in operations, and development of new process and production structure. This therefore require that the management propose and implement a strategy to optimize production based on its current production data and procedures. This study therefore developed the strategy to optimize the production of a knitting plant by first reviewing the production data, identifying the failures, conducting the root-cause analysis, proposing a solution, and simulating the approach to determine the impact on the productivity. The result showed that the knitting plant system availability increases to 91.3% when simulated with a positive cost benefit analysis. This showed that the proposed strategy can optimize the knitting production plant without the need to implement industry 4.0 technologies and its challenges.

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