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Integrating a Green Lean Six Sigma Framework for Sock Manufacturing Operations in SMEs

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Abstract

The Green Lean Six Sigma (GLSS) approach represents a robust and integrative methodology for advancing quality and operational efficiency, as well as incorporating green practices to achieve sustainable improvement. This paper proposes a framework suitable for small and medium-sized manufacturing enterprises (SMEs). The framework utilizes the DMAIC cycle of Six Sigma, incorporating tools such as process mapping, cause-and-effect analysis, and Pareto techniques to enhance the quality and focus improvement efforts on the primary sources of inefficiency. Validation was carried out in a small Egyptian sock manufacturing company with limited financial resources to test the effectiveness of the proposed model. Implementation of GLSS initiatives has led to a 70% decrease in defect rates in the considered case, a rise in process sigma level from 1.26 to 1.86, and an increase in daily production by nearly 30%. Green practices were incorporated by minimizing material waste resulting from defective items. Compared to similar small-scale cases, the outcomes are quite satisfactory.

Keywords
Green Lean Six Sigma, DMAIC methodology, Textile manufacturing, Sustainability, and Small and Medium Enterprises (SMEs).

1. Introduction
Small and medium-sized manufacturing enterprises represent a fundamental core of most economies worldwide, offering significant contributions to employment, economic growth, and industrial development (Alexander et al., 2019). In Egypt, they represent 97.6% of total establishments and contribute nearly 72% of total employment and generate a total production value of EGP 1.24 trillion, representing approximately 32% of the country's production (CAPMAS, 2018). The manufacturing sector of SMEs is struggling with limited quality control, inefficient operational procedures, and a shortage of skilled workers, and tackling these problems is necessary to reach sustainable development (Qureshi et al., 2022). Lean manufacturing aims at reducing wasteful activities and optimizing workflow to attain peak efficiency. Lean uses tools like Value Stream Mapping (VSM), 5S, Just-In-Time (JIT), Kaizen, and Kanban. On the other hand, Six Sigma focuses on identifying and eliminating process variations and defect rates to near zero. Six Sigma uses DMAIC methodology and tools such as design of experiments (DOE), analysis of variance (ANOVA), statistical process control (SPC). "Green" often used synonymously with sustainability, refers to the environmental dimension of the sustainable development (Nagadi, 2022). Green manufacturing is defined as an operational physiology in which firms reduce their environmental footprint and enhance ecological efficiency while improving the organizational financial performance (Garza-Reyes, 2015). This is implemented through sustainable practices such as waste reduction, energy conservation, use of greener materials, and emission control (Shokri et al., 2020).Green Lean Six Sigma (GLSS) integrated methodology has been adopted worldwide by combining the operational efficiency of Lean manufacturing, the statistical discipline of Six Sigma, and environmental practices to

reach operational excellence through a unified framework, making it suitable for SMEs seeking strategies to improve their quality (Mohan et al., 2024; Rathi et al., 2022; Singh et al., 2021). However, the majority of GLSS literature revealed significant barriers including absence of standardized frameworks, lack of measurement metrics, limited management commitment, and resource constraints (Cherrafi et al., 2016; Siegel et al., 2019; Singh et al., 2021; Utama & Abirfatin, 2023). Therefore, practical frameworks are essential to advance GLSS implementation, particularly in SMEs, where environmental practices significantly intersect with operational excellence.

1.1 Objectives

The contribution of this research is to develop an integrated Green Lean Six Sigma (GLSS) framework for SMEs, following DMAIC methodology with the objectives of reducing defect rates, enhancing machine performance, and implementing sustainable improvements. The proposed framework has been validated through implementation at an Egyptian company specializing in sock manufacturing to test the effectiveness of the suggested model.

2. Literature Review

2.1 Lean Six Sigma Applications in Textile and Sock Manufacturing

Several studies have explored the application of Six Sigma methodologies alone to improve quality in the textile sector. For example, Ahmed et al. (2022) successfully applied Six Sigma in a knitting factory in Bangladesh, achieving a 51% reduction in defect rates, through tools like Pareto charts and cause-effect analysis. Similarly, Kurnia et al. (2021) used tools like Failure Mode and Effect Analysis (FMEA) and Key Performance Indicator (KPI) methods in the sock industry to reduce defect rates from 11.08% to 5.54%. Likewise, Sagar et al. (2020) applied it in a garment factory, cutting fabric defects from 10.07% to 7.87%. Furthermore, Jony Moin et al. (2023) identified the key garment defects in the knitwear industry by focusing on Total Quality Management (TQM) tools, highlighting poor operator skills and improper machine settings as root causes for the defects. Kurnia et al. (2022) utilized Plan–Do–Check–Act (PDCA) cycle and Overall Equipment Effectiveness (OEE), increasing OEE from 63% to 73% and boosting the machine output by 112%.

Cherrafi et al. (2016) showed that most LSS research in manufacturing concentrated on specific industries such as automotive (28.3%), followed by metal industries (13.2%), while textile industries received less attention at only 5.7%. In particular, Adrian et al. (2022) applied LSS in a knitting factory where 75% of produced fabric rolls needed rework, and they improved efficiency by 11.23%, shortened lead time by 15.13%, and increased profitability by 6.17%. Raj & Handayati (2024) also applied LSS at a polyester yarn producer, discovering poor quality control and training as root causes of yarn defects. They suggested standardizing inspections and staff training. Sheel (2025) improved process consistency, reduced rework, and enhanced product quality, elevating the sigma level from 2.7 to 3.0 in a ready-made garment firm.

2.2 Green Lean Six Sigma Applications in SMEs

Recent studies revealed that although GLSS applications in large companies have improved quality alongside with environment impact, the adoption within SMEs is still significantly scarce (Dahab et al., 2024; Mohan et al., 2024; Sheel, 2025). For instance, Rathi et al. (2022) developed a GLSS framework alongside social lifecycle assessments (LCA) and validated it in a large component fastening factory. The model reduced environmental impact by 26.4% as a result of reduced material, water, and energy consumption while improving process cycle time, and decreasing lead time by 22.47%, and 19%, respectively. Conversely, Helleno et al. (2017) integrated economic, social and environmental factors with the traditional indicators of lean VSM. Environmental KPIs targeted material, energy, and water use, along with waste generation, making the framework particularly relevant to green manufacturing. They validated the method in three Brazilian industries offering a useful detailed lean framework for sustainable improvement in SMEs. Moreover, Dahab et al. (2024), developed and validated a LSS framework for SMEs with environmental considerations which is mainly represented by reducing candle sooting and raw material waste in a small candle factory, using tools like 5S and VSM, they highlight potential for sustainable improvements in resource-constrained small enterprises.

In the textile sector, recent studies investigated Lean-Green integration. Some focused on direct environmental measures such as energy and water use. De-La-Flor et al. (2024) implemented it in the dyeing fabrics process because it had the worst performance in terms of water, energy, and rework. The approach yielded successful results in terms of performance and sustainability. In other cases, environmental practices can also be addressed indirectly. Delgado-

Angeles et al. (2024) improved workplace organization and reduced the defect by applying lean tools such as 5S and work standardization, thereby indirectly supporting sustainability through lower waste and better resource use.

The review of available literature reveals that green practices are still not incorporated into most Lean Six Sigma initiatives in the textile sector, although LSS has proven successful across numerous studies, particularly within SMEs in developing countries where financial and technological limitations exist. Therefore, this paper addresses this critical gap by developing and validating a GLSS framework in the textile sector, tailored for a sock manufacturing SME, thereby providing a practical and adaptable model to support sustainable performance improvement and process optimization within similar resource-constrained SMEs.

3. Proposed Methodology

The primary aim of this study is to develop a GLSS framework for SMEs that will help in tackling quality and efficiency issues. To ensure the effectiveness of the suggested framework, it was validated in a small Egyptian manufacturing enterprise. As shown in Figure 1, the proposed methodology follows DMAIC cycle, organized into three phases each applying relevant tools. In Phase 1, the Define step uses the SWOT analysis, process mapping and SIPOC diagram to establish a clear picture about the selected firm to test the potential for applying GLSS model and clarifying project goals. The Measure Step then employs tools like Environmental Value Stream Mapping (E-VSM) and sigma level calculations, which are essential for assessment of the current performance and facilitate waste quantification. In the second phase, inefficiencies are analyzed using tools such as brainstorming, fishbone diagrams and pareto chart to find out the root causes. After that, the improvement step emphasizes the identification and implementation of optimal corrective actions and demonstrates the enhancement achieved. Finally in phase 3, to sustain these corrective actions, a control plan must be created with a specific procedure that standardizes the work using a Standard Operating Procedure (SOP). In the subsequent sections, each step of DMAIC cycle will be discussed in detail, by breaking down the GLSS implementation process, this detailed overview will clarify how each stage contributes to achieving sustainable improvement.

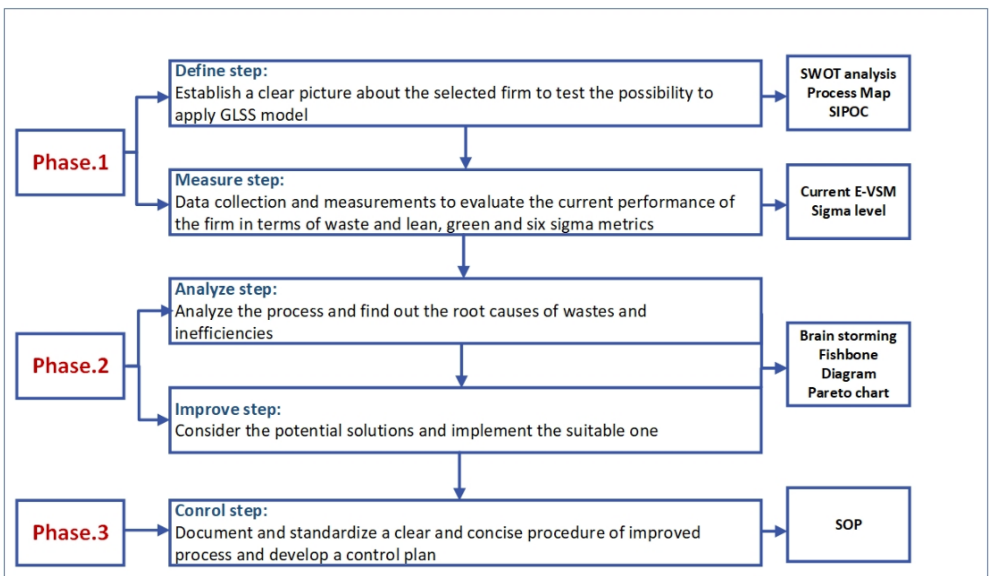


Figure 1. Proposed Methodology for Implementing the Green Lean Six Sigma (GLSS) Model.

3.1 Define Step

3.1.1 Case study overview

The selected case study is a private small textile manufacturing company located in Alexandria, Egypt, and was established in 2013. Employing around 150 workers, and the company focuses on knitting a wide range of socks. As recent literature highlights (Kurnia, Sihar, et al., 2021), there is a significant lack of research and application of Lean Six Sigma in the knitting segment compared to other textile sectors such as garment and weaving. The company holds a distinctive position thanks to the rareness of sock manufacturing in the region, which grants it a notable market position and potential strategic advantage. In addition to serving local clients, it also supplies socks to international brands and operates production lines that carry the brand name itself. Despite these advantages, the company faces several operational challenges. The most pressing issues include a high rate of defects, low productivity, a shortage of skilled operators, especially those able to work with advanced knitting machines as well as significant reliance on outsourcing key raw materials such as cotton, elastic, and nylon from abroad. These factors limit the company's ability to expand efficiently and maintain consistent quality, which is considered the biggest threat to its survival, keeping customers' satisfaction.

3.1.2 SWOT analysis

SWOT analysis was conducted through interviews with owners, managers, and customer feedback, aiming at identifying the key focus areas (Figure 2). The analysis illustrates that the company's strengths lie in its regional monopoly in sock manufacturing and E-commerce presence, but it has challenges linked to import dependence, high employee turnover, and external threats like economic instability and workforce instability. Finally, opportunities are highlighted in export growth, E-commerce expansion and building new strategic partnerships.

Figure 2. SWOT Analysis Highlighting Growth Opportunities and Operational Challenges for the selected company.

3.1.3 Process of sock manufacturing

The first step in the sock manufacturing process is receiving the customer's requirements and ensuring that the final product will meet design and quality expectations. Once customer details are collected, receipt of raw materials from suppliers takes place to begin the production process, as shown in the process map (Figure 3). Each batch passes through an initial quality control (QC) check, performing visual inspections for yarn quality, specifications, and color. After that, the yarn moves to the main operation of "knitting", where circular knitting machines start to knit the yarn into sock tubes according to the required size and pattern. During the knitting process, inspectors check for any defects, separating the output into first grade and second grade (defective) and reporting repetitive issues to a maintenance technician to inspect the machine. Next, the socks move to the toe linking machines, where the open toe sock is sewn closed. This method ensures comfort by minimizing bulky seams. Socks are then manually trimmed to remove any excess threads. Finally, in the boarding operation, socks are ironed and shaped on a suitable metal form under a controlled temperature and for a specific time to define the sock's final appearance. A final quality inspection takes place after boarding operation, with examination of socks' size, appearance, and quality. Once quality is approved, packaging is done according to customer specifications using several materials such as, header cards, stickers, hooks, clips, polybags, and cartons. Finally, the packed socks are sent to the warehouse waiting for shipping to customers. In addition to process mapping, SIPOC diagram is created to highlight the essential connections between suppliers, inputs, and customers, providing a high-level snapshot of the process (Figure 4).

3.1.4 Data Collection

At the start, firm-wide historical data on defective percentage and daily production (Jan 2023 - Aug 2024) was collected to establish a performance baseline. The study was then focused on examining a specific sock model produced on nine different machines during October 2024, which allowed for the selection of the highest-defect machine for implementation. To precisely quantify the improvements, an initial defect frequency analysis was conducted via a 100% inspection of a production lot (Oct 23 - Nov 3, 2024). After implementing the corrective actions, a post-implementation analysis was carried out by inspecting the next full production lot (March 2–5, 2025).

Given the natural variation in lot sizes driven by customer orders, proportional quality metrics like defect rate and sigma level were utilized to maintain a valid and comparable assessment.

3.2 Measure Step

3.2.1 sigma level calculation

Based on the available monthly defect rate record from January 2023 to August 2024. Defect rates fluctuated between 9.70% and 14.45% with an average of 11.84% and a standard deviation of 1.36%, this fluctuation indicates unstable production process and the need for identifying root causes to implement the suitable corrective actions. However, the record didn't consider the type of defect, it is used only to calculate the overall sigma level for the company. In the next stage a classification of defects will be created to aid in pinpointing causes.

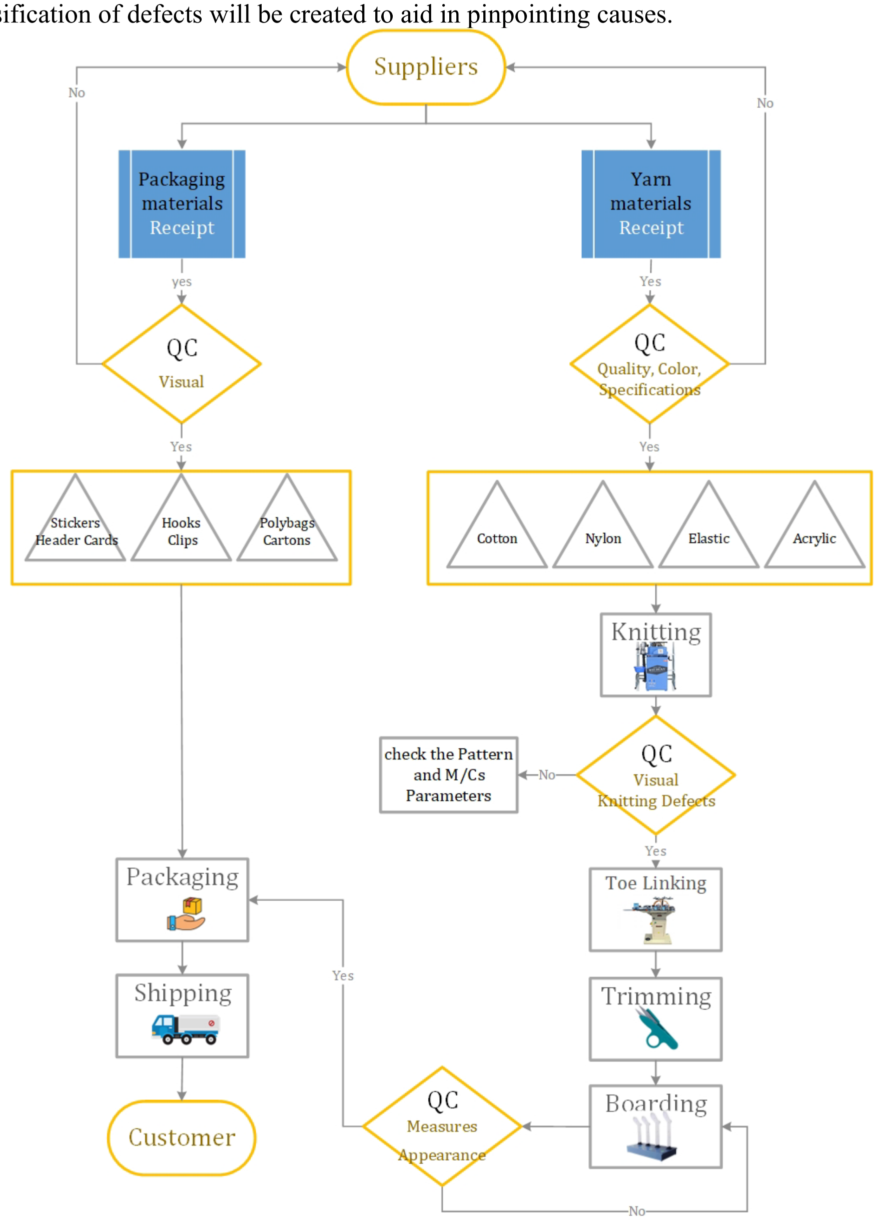


Figure 3. Process Map of the Sock Manufacturing at the selected company Highlighting Quality Control (QC) Checkpoints from Raw Material Sourcing to Customer Delivery.

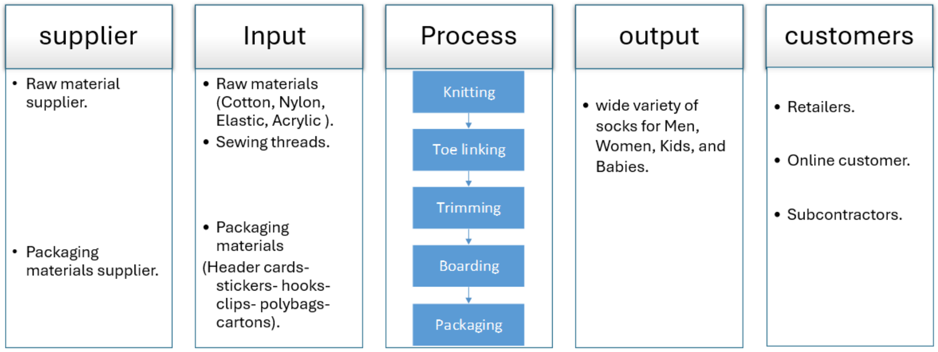


Figure 4. SIPOC Diagram for Sock Production in the Selected Firm.

Sigma level was calculated as follows:

Total production checked	=76761.42 kg	
Total defects	= 9089.27 kg	
Defect per unit (DPU)	$= \frac{Defects\ (kg)}{Total\ production(kg)}$	= 0.1184
Parts per million (PPM)	$= DPU \times 10^6$	=118409.32
Sigma level (Z)	$= \emptyset^{-1}(\frac{PPM}{10^6 \times 2})$	=1.56 σ

3.2.2 Value Stream Map

A value stream map (VSM) was developed to highlight each step from raw material receipt to shipment. The aim was to visualize the process and identify inefficiencies and the areas for potential improvement (Figure 5). The VSM shows the material flow, process cycle, change over time for each process measured per unit of sock, and the available number of machines and operators. Moreover, it detects the percentage yarn waste across the knitting and boarding stages by 6.84% and 5% respectively. This study focuses on reducing material waste to integrate green practices within the sock manufacturing process, emphasizing the significance of managing resources responsibly to attain sustainable improvements in the textile industry.

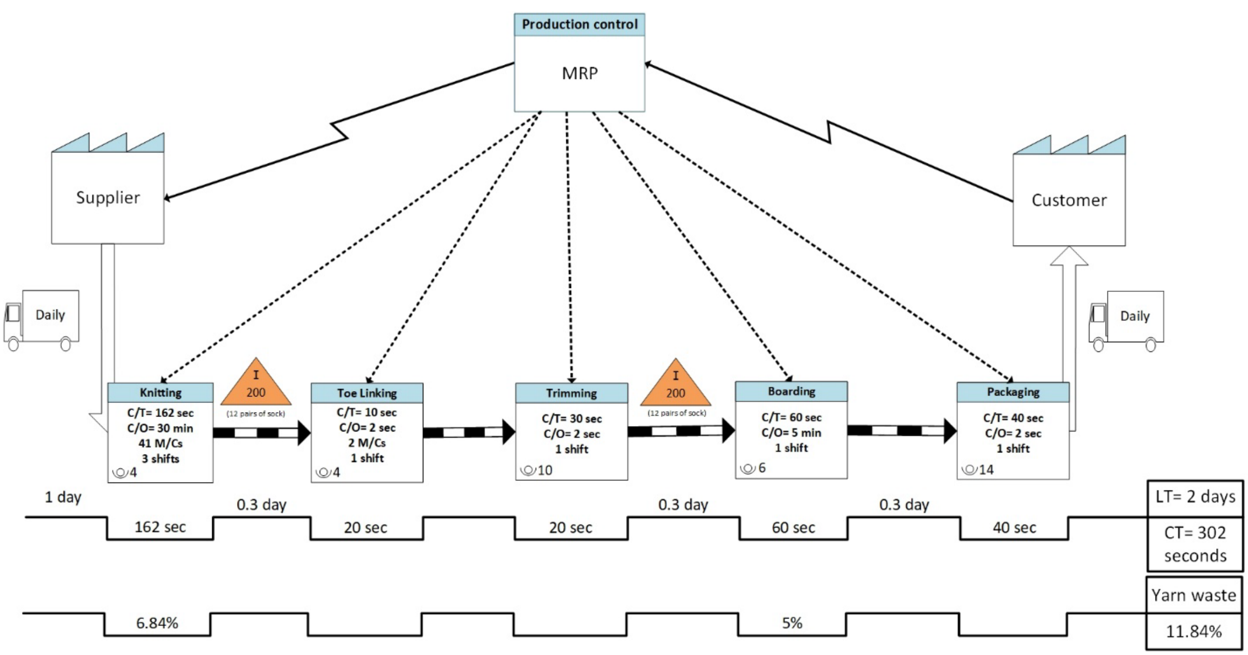


Figure 5. Environmental VSM Showing Current-State Operations in the Selected Case Study.

The VSM showed that the knitting operation is the primary bottleneck with a cycle time of 162 seconds per sock, significantly higher than subsequent stages. Despite the knitting department operating three shifts per day, actual daily production continues to fall below the target. The actual daily output varies depending on the machine type, especially the cylinder's needle count, which is responsible for sock sizes specified in customer orders. In conclusion, the average target was 685 dozen, while the actual production average was 557 dozen, which means the firm needs to increase capacity by at least 25% to meet customer demand.

3.3 Analyze step

At the beginning of the Analyze step, it was essential to focus on a particular sock type that has significant business importance and quality challenges, as well as to focus on a certain machine in order to minimize the variation sources to identify the root causes of defects. After discussions with factory management, the "Long Lycra - man size" sock was chosen, subsequently, defect percentages were evaluated across all 9 machines producing this sock type. Machine 35 was selected as it recorded the highest production volume and the highest defect rate (Figure 6).

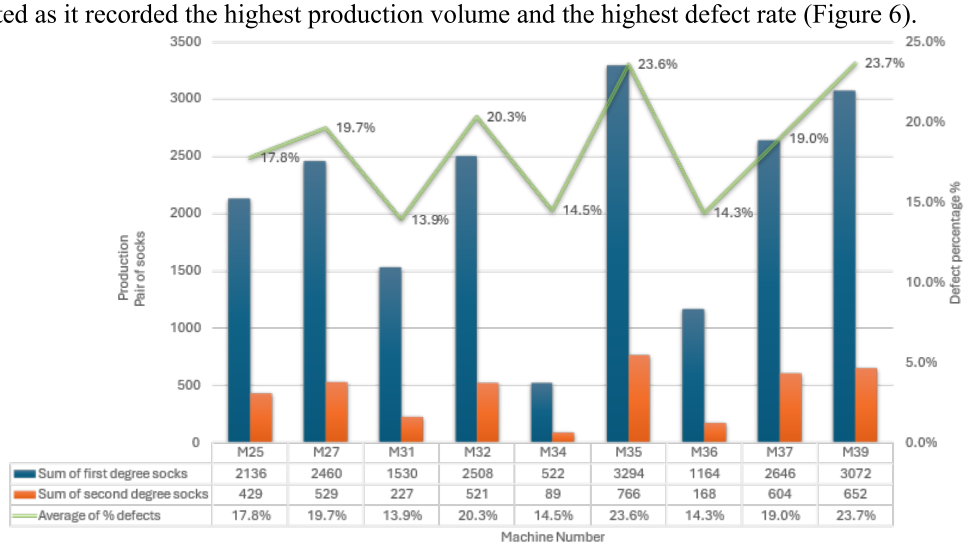


Figure 6. Output and Defect Analysis of Nine Machines Producing "Long Lycra – Man Size" Socks During October 2024.

A defect frequency analysis was performed on Machine 35; 618 defective socks were recorded out of a total of 2964 inspected lot; the average defect rate was 20.85% with a standard deviation of 20.26% with five types of defects summarized in Table 3. To further clarify the distribution of defects, a Pareto chart was constructed (Figure 7), highlighting that most defects were elastane drop, and sinker mark which accounted for 86% of total defects and were prioritized for deeper root cause analysis.

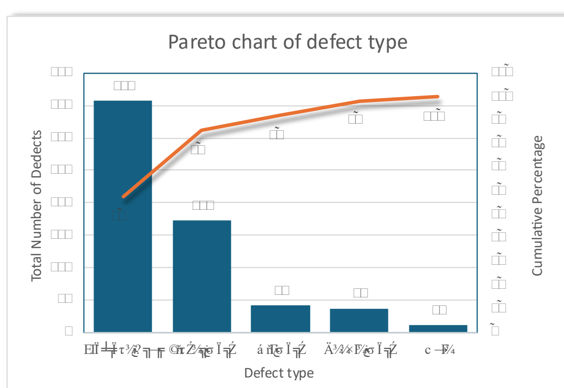


Figure 7. Pareto Analysis Highlighting the Most Frequent Defect Types in the Selected Knitting Machine.

A group brainstorming session was conducted. floor production manager, industrial engineer, quality supervisor, and maintenance technician attended the session. The outcomes of the discussions are illustrated in the attached fishbone diagrams, Figure 8 and Figure 9, for the dropped elastane defect and the sinker mark defect, respectively. The team prioritized two root causes for the dropped elastane defect: inefficient feeding technique (Method) and no control over the elastane tension (Measurement). Additionally, three for the sinker mark defect: the lack of lifespan tracking (Measurement), damaged sinkers (Machine), and operators being busy with repairs (Man). Other potential causes were excluded from the prioritized list as they are not easily controlled or modified within the current firm situation. As a next step, appropriate remedies were suggested for all causes obtained in the brainstorming session. Feasible solutions were implemented to the prioritized causes, and effectiveness evaluated by monitoring changes in the defect rates at the same machine and sock model selected.

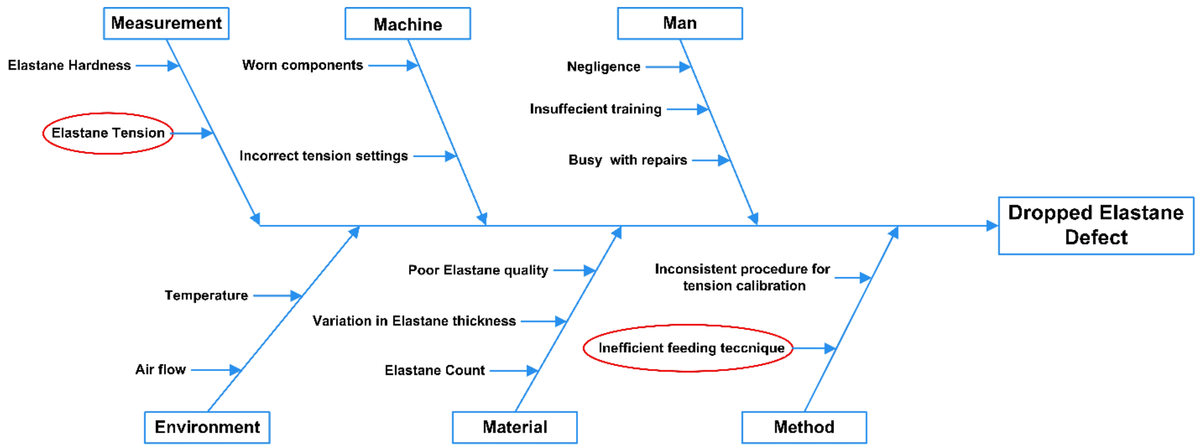


Figure 8 Cause-and-Effect Diagram for Dropped Elastane Defect.

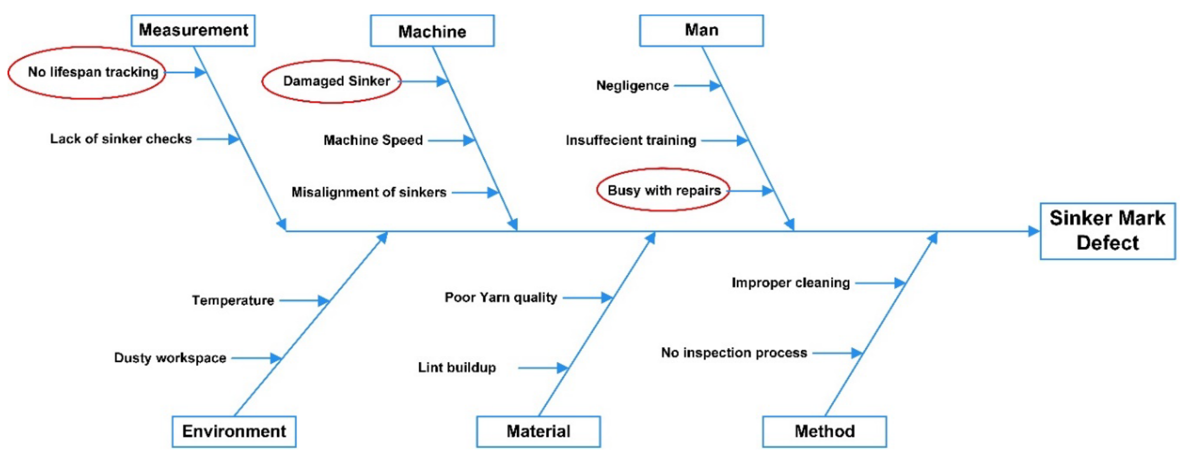


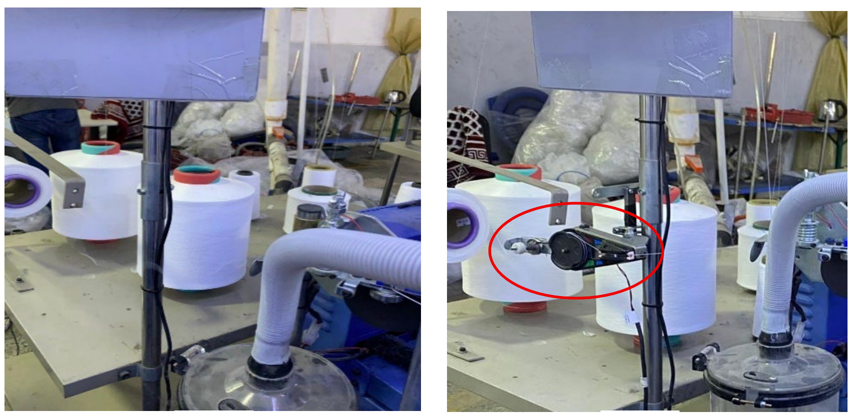
Figure 9 Cause-and-Effect Diagram for Sinker Mark Defect.

3.4 Improve step

Based on the prioritized root causes identified in the Analyze step, a set of corrective actions was implemented to decrease the defect rates for both types (Table 1). These actions were selected for their feasibility and expected effect on the quality. In sock knitting, it is crucial to control elastane tension, as any fluctuations can lead to fabric defects like dropped elastane and poor elasticity of the fabric. The suggested solution was to find a device to control the tension. Therefore, a technical comparison of three yarn feeder devices was conducted: *Mini Yarn Storage Feeder, Electronic Yarn Storage Feeder, and Keep Tension Yarn Feeder.* According to specific features such as compatibility, speed, weight, and design. The Keep Tension Yarn Feeder was selected as the most suitable device; it offers automatic yarn tension adjustment and high-speed capability. Figure 10 shows the actual installation of the selected yarn feeder at knitting machine No.35.

Table 1. Summary of Implemented Corrective Actions

Problem/Area	Action Taken	Type
Sinker Mark Defect	Replaced worn sinkers of machine No.35.	Green/waste
	Started lifespan log and proactive replacement cycle.	Operational
Dropped Elastane Defect	Attached “Keep tension yarn feeder” to machine No.35.	Green/waste
Operator/Staffing	Provided two hours of weekly training for new staff.	Operational



(a) (b)

Figure 10. Knitting Machine 35 (a) Before, (b) After Attaching the Keep Tension Yarn Feeder.

The sinker is a fundamental component in the knitting operation, responsible for precisely controlling yarn movement and forming loops through its interaction with the needle’s movement, directly impacting the quality of the fabric produced. All worn or damaged sinkers in the selected machine were replaced with new ones (Figure 11). The affordability and availability of sinker sets make large-scale implementation financially feasible, therefore the procedure scheduled to be implemented to all machines. In addition, a systematic sinker lifespan tracking log was introduced using an excel sheet. Installation and replacement dates for each group of sinkers will be recorded, enabling a proactive replacement cycle based on operational hours rather than defect occurrence.

(a) (b)

Figure 11. Sinker Condition in the Selected Machine: (a) Worn sinker, (b) New Sinker.

The company independently undertook the following managerial initiatives. To address issues related to operator workload and productivity, four extra operators were assigned to the knitting department to reduce the incidence of operators being too busy to monitor quality effectively. Moreover, to solve the persistent problem of missing daily production targets, four outdated knitting machines were scrapped and replaced with eight new machines, bringing the total to 45 knitting machines.

3.5 Control step

In the control step of the GLSS implementation, a standard control plan was established to sustain the previous improvements achieved through the implementation of a dedicated standard operating procedure (SOP) covering all key stages from raw materials inspection to final packaging. Detailed logs and checklists using excel files were initiated to monitor and document the critical parameters like sorting the defect types for all machines, yarn tension settings with the new feeder installed, and sinkers and needles replacement cycles. The firm also scheduled periodic training for operators and quality staff to reinforce adherence to new procedures. Monthly review meetings were established to analyze defect trends. By embedding these practices, the firm ensured that quality improvements will be maintained, and the root causes of defects proactively tackled, and a continuous improvement culture encouraged across the entire organization.

4. Results and Discussion

This section presents the outcomes of the implementation of the proposed improvement actions. First the defect rate, sigma levels are recalculated for the machine (No.35) after improvement. Subsequently, the Pareto analysis is performed again to clearly illustrate the impact of improvements on defect distribution. while the firm's daily production calculated again and compared with its preceding average value. By comparing these results, we can test the effectiveness of the proposed GLSS framework in reducing defects and enhancing the firm's performance. The study's results revealed significant improvements. Defect rates decreased from 20.85% to 6.16%, the sigma level according to the selected machine increased from 1.26 σ to 1.86 σ, and daily production improved by almost 30% (Table 2). Such enhancements prove the effectiveness of the proposed model in tackling quality and efficiency issues. The defect analysis also highlighted the benefits of directing efforts toward dominant defects by means of pareto analysis (Figure 12). The elastane drop defects were eliminated entirely, which considered the primary contributor of total defects, while sinker marks decreased from 172 to only 4 cases. The remaining defect types, such as oil marks and needle marks, persisted at lower levels and represent areas for future improvement (Table 3).

Table 2. Comparison of Key Operational Performance Metrics Before and After GLSS Framework Implementation.

KPI	Before improvement	After improvement	Improvement %
Overall defect percentage	20.85%	6.16%	70.46%
Sigma Level	1.26 σ	1.86 σ	48.05%
Daily production	557 (12 pairs of socks)	724 (12 pairs of socks)	29.98%

The 70% reduction in defect rate achieved in this study demonstrates that targeted corrective actions, such as yarn feeder installation, systematic sinker replacement, and operator training can deliver improvements that meet or exceed outcomes documented in related industries. For instance, (Ahmed et al., 2022; Kurnia et al., 2021) each reported reduction in defect rates closer to 50% by implementing six sigma strategy alone. This emphasizes GLSS as a practical option for SMEs with limited resources.

Table 3. Classification of Defect Types Before and After Improvements

Defect Type	Number of defects before improvement	Number of defects after improvement
Elastane Drop	357	0
Sinker mark	172	4
Oil mark	41	38
Needle mark	37	28
Hole	11	23
Total	618	93
Lot size	2964	1509
Percentage%	**20.85%**	**6.16%**

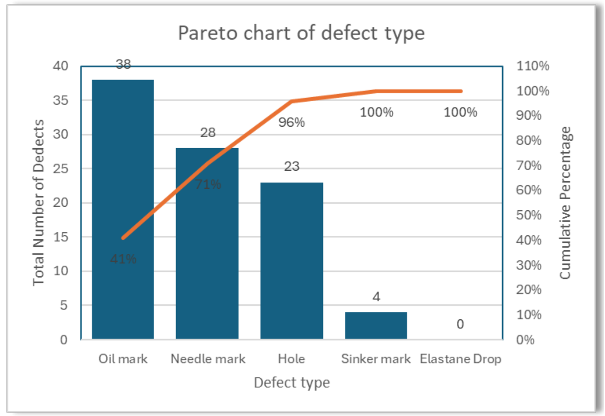


Figure 12. Pareto Analysis Types in the Selected Knitting Machine After Improvements.

The implemented solutions delivered benefits beyond improving the quality and performance of the company, extending to green practices. Waste was reduced by attaching the yarn feeder to control the tension and replacing the worn sinkers, and outdated knitting machines were replaced with modern models to increase the capacity while lowering energy consumption. This combination of process efficiency with resource efficiency reflects the green dimension of the framework and emphasizes its dual function in promoting both performance and sustainability. Overall, the findings showed that GLSS offers a practical methodology to improve both quality and operational efficiency while also considering environmental pillar of sustainability, even for constrained financial SMEs.

5. Conclusions

The implementation of the proposed GLSS framework on the selected machine successfully identified the root causes of the major defects, namely dropped elastane and sinker mark. The corrective actions raised the sigma level from 1.56 σ to 1.86 σ by reducing the defect rate. These gains demonstrate the framework's 'Green' component quantitatively. The 70% reduction in defect rate provides a direct measure of environmental impact, translating to a significant reduction in material waste (yarn) and the energy that would have been consumed to produce those defective items. Significantly, the successful pilot study on Machine 35 motivated management to implement the corrective measures across the entire factory. The operational efficiency has improved as daily production output increased by 30**%** as a result of management's upgrades in equipment and workforce, allowing the firm to meet customer demand and eliminate order delays. This case study successfully validated the model's effectiveness in a single sock manufacturer, providing a strong foundation for future research into its scalability across other sectors. Future research should, therefore, focus on applying the framework in different manufacturing sectors, such as food processing or assembly. This would require adjusting environmental metrics and improvement tools to suit each industry's specific challenges, thereby expanding the framework's applicability.

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