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A Framework to Enhance Green Factories by Applying Lean Production Concepts: A Review

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A B S T R A C T

This research discusses the integration of Lean Manufacturing (LM) and Green Manufacturing (GM) as a cohesive strategy for enhancing operational efficiency and environmental sustainability. The review, informed by recent empirical studies, illustrates that fundamental Lean tools—such as 5S, SMED, Kaizen, Root Cause Analysis, Value Stream Mapping, and Just-in-Time—consistently diminish non-value-added activities, augment workflow stability, and enhance productivity across various industrial sectors. These operational improvements directly result in environmental advantages, including reduced energy use, diminished CO_2 emissions, lowered water usage, and minimal material waste. While Lean Manufacturing (LM) and Green Manufacturing (GM) share core tenets of waste reduction, the literature highlights various discrepancies, including the environmental impact of frequent changeovers, heightened logistical emissions from Just-In-Time (JIT) systems, and the embodied energy associated with the duplication of Single-Minute Exchange of Die (SMED) tools. The paper tackles these difficulties by presenting a cohesive Lean–Green paradigm, emphasizing Industry 4.0 technologies as essential facilitators of real-time monitoring, predictive maintenance, and resource-efficient optimization. A pragmatic roadmap is offered to assist small and medium-sized organizations (SMEs) in the cost-effective implementation of Lean–Green practices. The synthesis highlights the strategic importance of Lean–Green integration and provides prospective research avenues for quantifying environmental consequences and evaluating digitally enabled sustainability enhancements.

K E Y W O R D S

Lean Manufacturing; Green Manufacturing; Lean–Green Integration; SMED; 5S; Value Stream Mapping; Industry 4.0; Sustainability.

1. INTRODUCTION

Manufacturing firms are increasingly pressed to increase operational efficiency while simultaneously decreasing their environmental effect. This twin problem has encouraged the growth of integrated improvement concepts such as Lean Manufacturing (LM) and Green Manufacturing (GM). Although LM has typically focused on removing non-value-added operations to boost productivity and reduce costs, accumulating data suggests that many Lean methods intrinsically contribute to environmental sustainability when used consistently. Lean tools such as 5S, SMED, Value

Stream Mapping (VSM), and Kaizen have showed demonstrable benefits in workflow stability, defect reduction, and energy savings across varied industrial contexts.

At the same time, recent research has highlighted the growing importance of environmental stewardship within industrial systems. Green Manufacturing attempts to reduce ecological burdens—such as energy use, carbon emissions, water usage, and solid waste—across the product life cycle. Several studies emphasize that LM and GM share a same foundation in waste minimization. Integrating these approaches can generate mutual benefits: Lean's focus on process efficiency typically fits with Green objectives such as resource conservation and pollution reduction. Combined Lean–Green applications have been shown to reduce environmental waste and increase sustainability performance in several industrial contexts, including construction, food production, and packaging manufacturing.

This has resulted in the emerging notion of the Green Factory—a manufacturing system that combines Lean principles with environmental sustainability to attain both economic and ecological efficiency. This review employs the term "Green Factory" to encompass all comparable ideas identified in the literature, such as Eco-friendly Plant, Sustainable Factory, and Environmentally Responsible Manufacturing System. A Green Factory, as delineated in this document, is a manufacturing system that methodically employs Lean methodologies to diminish operational waste while integrating environmental indicators to curtail energy usage, emissions, resource use, and ecological footprint. This definition delineates the parameters of the evaluation and embodies the dual objectives of efficiency and sustainability. K. Jbira et al. [144] further proved that Lean methods can directly promote the expansion of Green manufacturing by enhancing workflow stability and eliminating resource-intensive activities.

Despite these synergies, synchronizing LM and GM is not always straightforward. Several assessments emphasize conceptual ambiguity and practical impediments, particularly in regard to Lean–Green tradeoffs, organizational constraints, and the lack of integrated frameworks to guide implementation. Moreover, recent case studies highlight the significance of systematic methodologies—such as DMAIC, VSM, and life-cycle assessments—to precisely measure both operational and environmental results.

This review synthesizes existing literature on Lean and Green Manufacturing, evaluates the contribution of Lean methods to environmental benefits, and highlights significant gaps that impede the implementation of a cohesive Lean & Green (L&G) framework. The paper analyzes empirical findings from manufacturing, construction, food processing, and textile industries to offer a comprehensive knowledge of the effective integration of Lean Management (LM) and Green Management (GM) for achieving sustainable operational excellence. The insights generated herein seek to assist both scholars and practitioners in progressing the Lean–Green paradigm and constructing more resource-efficient, ecologically sustainable manufacturing systems.

2. ESSENTIAL LEAN TOOLS

2.1. Five "S"

A business strategy that is mostly employed by Japanese companies, the 5S method increases production efficiency and makes a substantial contribution to industrial output and export earnings. Seiri (sort), Seiton (put in order), Seiso (shine), Seiketsu (standardize), and Shitsuke (sustain) are its five constituent parts. By keeping an eye on the organizational environment, this practice maximizes workplace organization, minimizes waste, and raises overall quality and productivity.

V. Mehta et al. [1] showed that a manufacturing company's productivity increases as a result of effectively implementing the 5S approach. Since the 5S enhances environmental performance, it mostly related to reducing production waste. Additionally, by arranging the items in a certain sequence, the placement of the goods was fixed and could be quickly evaluated, saving time spent looking. Other measures were also put in place to improve the institute's general working conditions. The quick results of 5S encouraged employees to practice self-discipline while working.

E. Vargas Crisóstomo [2], Prior to implementing Lean Manufacturing, a baseline or diagnostic study of 5S was conducted, yielding an initial average value of 2.8. By cutting down on needless time spent looking for supplies and moving workers, as well as by making the aqueous adhesives production environment more orderly and cleaner, the 5S application ultimately produced an average audit result of 4.03.

The degree of production process delayed before and after the adoption of 5S, standardization, and TPM tools was analysed by S. Pawlak [3]. The outcomes confirmed the beneficial effected of applying LM approaches on the production environment and allowed for the presentation of the magnitude of changes, i.e., reductions in delay times.

K. Arun et al. [4] concluded that the use of 5S increased industry efficiency while simultaneously improving worker comfort. A workplace that was tidy, well-organized, and uniform made working more comfortable and produced fewer errors. Implementing lean manufacturing reduced waste and increased customer satisfaction. The application of 5S could also lead to an increase in process variability and increased productivity, which benefits industry. The successful application of 5S in the pump manufacturing sector was validated by the observed improvements in the percentage rises in the manufacturing industry across many sectors.

According to A. Makwana et al. [5], the adoption of the 5S technique had significantly enhanced staff morale and work culture. The outcome showed a significant decrease in the materials' search time. The search time was 3.1 hours instead of 8.6 hours. The assembly time had improved as a result of the search time being reduced. Additionally, the assembly line had been enhanced and resource utilization had become more effective and efficient with the use of 5S. Additionally, the study demonstrated that the 5S level and productivity level were positively correlated and that the null hypothesis was rejected. The productivity level rose from 75% to 101% as the 5S level changed monthly, while the 5S score went from 20% to 80%. According to the study, an organization must have a strong momentum in order to consistently implement the 5S. Additionally, it should be noted that employee and 5S coordinator involvement is essential to the successful implementation of 5S.

M. Islam et al. [6] reduced waste and motion to improve manufacturing processes. Their study began with an understanding of poly bag manufacturing processes, then assessed process gaps and created a detailed 5S checklist to maintain standards. Maintaining blowing sizer and printing block storage racks was necessary. An improved storage system reduced needless movements to find operating instruments. The 5S approach reduced sizer searching time by 8% and block searching time by 18% for plastic bag printing. Sizer searching and lifting accounted for 4.40% of blowing operational time (formerly 12.12%), reducing block searching and setting time by 20.40% (previously 34.78%). This eliminated excessive motion and waiting time from both procedures and created a cleaner work environment. Customer printing complaints dropped from eight to one after 5S was implemented for three months. That time, 5S reduced needless motions and printing waste by grouping blocks. Following ergonomics, the heavy-weighted large sizers and tiny sizers were separated to ensure worker safety. A positive production environment required 5S housekeeping. 5S training had indirectly enhanced workers' confidence, which will lead to self-motivated workplace improvements that can boost the industry's gross profit. The audit team created and managed the audit procedure and timeline.

Kapil Gupta [7], reviewed previous research on 5S′application in various workplace situations. The following inferences were possible: Five S's had been shown to be a useful method for managing or organizing the workplace. Implementing 5S could significantly increase efficiency and production. Since Shitsuke was in charge of upholding the preceding Ss, its implementation was both crucial and difficult.

− One major issue that could make the adoption of 5S less successful was a lack of enthusiasm and involvement. The 5S, regular evaluations, training, and reviews were crucial.

− Adding safety as the sixth S and extending 5S to 6S were also suggested.

S. Muotka et al. [8] found that combining the 5S methodology with Design Thinking improves manufacturing work environments by making them safer, more organized, and efficient for employees. The 5S system removed unnecessary tasks and improved workspace functionality, while Design Thinking helped understand workers' needs and develop solutions through prototyping and feedback. This approach focused on process improvement rather than quick fixes, though some solutions needed more time to test. The results suggested that integrating 5S and Design Thinking was effective for solving complex workplace problems and could be beneficial in other Lean management areas.

M. Azad [9] examined how lean manufacturing affected textile mill efficiency and cost. Lean tools like 5S, Kaizen, JIT, and VSM resulted in significant improvements in key performance indicators, including lower production costs, defect rates, shorter lead times, and better inventory turnover. Without major capital investments, lean implementation eliminated non-value-adding activities and improved workflow efficiency. Even in resource-constrained contexts, lean lowered production costs by 20% and lead times by 30%. Importantly, lean success required human participation. Kaizen encouraged everyday improvements through employee participation, while management support and training helped overcome opposition and align department goals.

J. Roy Balinado et al. [10] demonstrated that 5S positively impacts automotive service operations in terms of employee performance, productivity, and workplace safety. Following the 5S approach (Sort, Set in Order, Shine, Standardize, and Sustain) would cut costs, enhance quality, productivity, and safety. In the service industry, client happiness was crucial, and 5S can aid in achieving this goal. Toyota Dasmarinas-Cavite must strictly implement, monitor, and educate its employees on the 5S practice and benefits to maintain its value.

J. Zvidzayi [11] found that successfully adopting Lean Management requires first assessing its suitability and building trust in its effectiveness, as failing to do so can hurt performance.

Understanding how 5S works with other Lean tools is crucial; without this, organizations risk more problems and failure. For 5S to be effective and sustainable, its strengths and weaknesses must be properly understood and applied. When implemented with Total Productive Maintenance and worker empowerment, 5S eliminates inefficiencies like waste and delays, significantly boosting efficiency. Achieving all Lean benefits depends on overcoming barriers, ensuring good resource management, clear processes, smart layouts, and full employee engagement, not just leadership. However, skill gaps and poor information flow can still pose challenges, as genuine cultural change requires participation from everyone.

2.2. SMED

SMED, or Single Minute Exchange of Die, is a key Lean Manufacturing technology that saves time and money by minimizing setup periods and waste. Companies who use SMED correctly see more frequent modifications, lower inventory, greater flexibility, and improved product quality. Its goal is to convert as many internal jobs as possible into external ones to conduct them without interrupting operations, using single-digit minute times. [12]

I. Hussain Zaidi et al. [13] examined internal and external changeovers, value-added and non-value-added activities, and productivity. This study addressed crucial production system factors like changeover and suggested ways to shorten changeover time to address the longer changeover time issue. It also highlighted changeover delay-causing actions. The flatbed printing machine changeover time was 142 minutes before implementing SMED, a lean technique, and eliminating the changeover challenges. Now it's almost 117 minutes. It indicated changeover time was shorter.

G. Santos et al. [14] improved cutting line setup by reorganizing staff, labeling and placing tools, and providing clear instructions. Record sheets were placed by machines for reference, and tools were duplicated or modified as needed. In AF2, although setup time slightly increased from 64 to 66 minutes, this was accomplished with one fewer worker than before. In AF3, setup time dropped from an average of 42 minutes to 22 minutes—a 24% reduction—achieved by a single operator. These changes streamlined processes and reduced manpower needs while improving efficiency.

S. Tetouani et al. [15] showed that using Lean Six Sigma, SMED, and fuzzy logic can greatly reduce mold changeover times in plastic injection molding. Their approach cut changeover time by 65%, increased Process Cycle Efficiency from 27.5% to 72.5%, boosted value-added time by 59.3%, and reduced non-value-added tasks by 71.9%. These improvements led to better equipment availability and overall manufacturing efficiency. The results demonstrated that Lean and modern tools can significantly enhance production performance. As competition increases, manufacturers are investing in lean strategies like these to reduce waste, improve supply chain efficiency, and stay competitive, especially by making machine changeovers faster to support flexible, high-volume production.

V. Parwani et al. [16] reduced SMED switching time. Our solution eliminated external tasks and converted internal activities to external, then utilized job scheduling to provide the easiest and most optimized job list to save changeover time. Similar activities were grouped and temporal lags were reduced in the model formulation. The approach used production planning and scheduling heuristics to detect and reorganize workers to reduce changeover time. The model suggested repurposing manpower to reduce lag between activities and creates an optimized operating process with a greater benefit-to-cost ratio (7.5) than the case study's 5th SMED stage (1.2).

L. Silva et al. [17] found that the main benefit of the SMED method is increased productivity, with 67% of studies reporting this advantage and die change times reduced by up to 49.43%. Other gains included improved flexibility, quality, cost savings, and smaller lot sizes. Long die change times were mainly due to poor work methods and insufficient employee training. In spring bed manufacturing, waste analysis eliminated five non-value-added activities, reducing production time. Systematic Layout Planning (SLP) led to two new plant layout options, both decreasing process steps and travel distance. Alternative layout 2 was most effective, reducing total operation time by 8.95% and travel distance by 56.77%, and was ultimately selected for implementation.

A. Ali [18] found that implementing SMED in spring bed production reduced setup time from 710 seconds to 434 seconds—a 38.86% decrease—by moving activities like material retrieval outside the setup process and allowing some tasks to be done in advance. Efficiency improved significantly in various production stages, and the new layout further reduced lead time by 39.58% (from 720 to 435 seconds).

I. da Silva et al. [19] showed that applying Lean tools through the SMED method drastically reduced machine setup time—from 1 hour 44 minutes 56 seconds to just 8 minutes 52 seconds, a 91.6% improvement. This made equipment available for production much sooner and increased Overall Equipment Effectiveness (OEE) to 44.6%. Key factors in achieving these results were staff training, standardizing setup procedures, monitoring setup times, and tracking OEE. The study suggested this approach can benefit industries needing frequent setups, such as electronics, chemicals, food, pharmaceuticals, and aviation, improving productivity, delivery times, and customer satisfaction.

P. Ołów et al. [20] found that providing CNC operators with barcode readers to load programs directly from workpiece labels and using standardized tooling significantly reduced machine changeover times. These technical and organizational improvements cut changeover times by 25% for the Phantomatic M3, 23% for the Comet T6, and 21% for the Satellite Xt. Further workstation reorganization led to even greater reductions—61% for Satellite Xt, 52% for Comet T6, and 12% for Phantomatic M3. Barcode scanning accelerated program loading by an average of 88% across all machines.

Nelfiyanti et al. [21] improved changeover processes on a stamping production line by analyzing operations for inefficiencies and applying Lean techniques, SMED, and simulation tools. They combined SMED with Lean tools, five Whys analysis, and WITNESS simulation to address root causes, resulting in the ISMED framework. This approach reduced changeover time by 62.2% and increased output by 37.5%. The ISMED framework is a key innovation that can help other industries enhance changeover efficiency and productivity.

S. Marcella et al. [22] found that replacing a 9" Crystal plate mattress originally took 236.96 minutes across 36 mostly internal steps. By streamlining the process, shifting internal steps to external ones, and recalculating standard times, setup time was reduced by 30.63 minutes—a 16.68% decrease. This confirmed SMED as the most effective method for improving mattress replacement efficiency. The study recommended ongoing SMED training, standardized setup procedures, and routine maintenance to maintain efficient and reliable operations.

M. Rahman et al. [23], The initiative sought to reduce changeover time, boost productivity, lower inventory, and meet delivery deadlines. Understanding plastic manufacturing, flow injection moulding, and standards is essential. SMED can cut changeover time by 18–33%. Compared to case-2, changeover time decreased 33%. If we invest in mechanical devices, especially for internal exercises, changeover time may decrease. A shorter changeover time saves money in preparation time, conveyance speed, type, and consumer loyalty. Any company can experience the constraints that have limited this performance, but persistence is needed to improve flexibility and assembly.

A. Mohammad et al. [24] found that SMED significantly reduces changeover times and boosts production in the garment industry, helping suppliers meet demands for cost reduction, smaller lots, and faster delivery. The benefits of SMED outweigh the investment, especially when tailored to the specific needs of factories in developing countries and combined with simple lean tools. Using frameworks like RACI to clarify responsibilities ensures better coordination and commitment. The study showed that implementing SMED and RACI had no negative effects in three factories. For best results, practitioners should integrate SMED with planning systems and use it consistently across production lines, especially as digitization grows in developing nations.

M. Braglia et al. [25] introduced Set-up Saving Deployment (SSD), a new lean tool that helps identify and eliminate set-up losses during changeovers, boosting efficiency and aiding SMED decisions. SSD uses three matrices to pinpoint losses, assess time savings, and recommend corrective actions. In a case study, SSD standardized set-up tasks and improved set-up efficiency by 72%, cutting transition time from 1070 to 210 seconds. The tool's structured design makes it easily compatible with business software and Industry 4.0 systems for real-time monitoring and electronic implementation across the plant.

J. Nikoli [26] found that applying the SMED technique reduced short OEE stoppages during setup and changeovers, minimizing downtime and extending production cycle times. A 16-minute SMED approach saved time, boosted output and running speed, and improved OEE by 2.83% at Trim Ltd. While mainly used to cut machine downtime, SMED can also address other OEE losses. The study highlights the need for more research on production OEE metrics and recommends that Lean businesses, especially SMEs, use SMED to tackle various OEE issues in real manufacturing settings.

R. Sahin [27] used the SMED methodology to develop an optimal standard process for production line changeovers, focusing on reducing internal preparation time and minimizing trial-and-error adjustments. At a ball bearing manufacturer, implementing SMED reduced trepanning line setup time from 1,418 to 930 minutes. When two operators worked together and shared tasks, changeover time was further reduced from 749 to 466 minutes. The study confirmed the effectiveness of SMED in ball bearing plants and suggested that managers apply these principles in other industries for similar benefits. Even small changes can improve competitiveness, resource efficiency, and production growth by adopting Lean methods like SMED. The report also recommended future research on integrating SMED and 5S with Industry 4.0 concepts to enhance efficiency in industrial and service sectors.

Using the SMED tool in Mexican body assembly improved planning and productivity by eliminating model setups on the production line, according to A. Juárez-Vite et al. [28]The company had no efficient setup model, so SMED was used to fill the void. In particular, the SMED technique adjusted the line so that the tools were ready to use, employed a car with all the tools to speed up setup, and used a folding reference device. Staff intervention synchronization was also adjusted. Applying SMED principles reduced setup time by 56% and facilitated rapid assimilation of suggested operations by operating personnel. The methodology has worked so far.

C. Perez Canchanya et al. [29] found that systematically combining SMED, Kanban, Standard Work, and other Lean techniques significantly improved production performance. Order fulfillment rose from 82.4% to 95.6%, a 13.46% increase. The pack arming cycle time dropped by 19%, and penalty rates fell from 17.6% to 3.15% (a 14.45% reduction). Process movement times also decreased by 10.33%. These improvements confirm the effectiveness of the integrated Lean model. Additionally, benefits like better people management and workflow were seen with Kanban, while Standard Work helped prevent confusion and negative fluctuations among staff. The approach fosters value creation, stability, innovation, and continuous improvement. However, the study notes that more comprehensive data collection and analysis are needed for deeper insights in the food industry.

2.3.Muda

Muda is waste, or actions that don't benefit customers. Shingo (1989) recognized seven lean manufacturing wastes; Liker (2004) in the Toyota guide added eight. MUDA 8 emphasizes operational inefficiencies such time waste, space waste, poor quality, higher expenses, and delayed deliveries. Operators should identify and fix waste causes to improve business efficiency.[30]

Dr. Annam Sunny Kumar et al. [31] emphasize that effective manpower utilization and line balancing are essential for manufacturing efficiency. Ensuring similar operator cycle times and evenly distributed workloads improves line efficiency. Their study shows that rearranging machinery and adjusting plant layouts increase efficiency, often by merging workstations and applying lean principles like waste elimination and cellular methods. These changes led to better material flow, less work-in-progress, improved workstations, reduced manpower needs, higher production rates, and less line imbalance. As a result, monthly completion rates rise, component transit times fall, and manual transportation is eliminated, optimizing assembly-line resources.

D. Birchit [32] identified that management typically addresses wastes from waiting, inventories, and defects, which are major contributors to increased manufacturing costs. Lean principles are crucial for eliminating these wastes, and quality management systems should be used for continuous improvement. In the company studied, the main wastes are waiting (for inputs, repairs, or previous outputs), storing reworkable materials, and defect correction, while wastes from overproduction, motion, over-processing, and transportation are less agreed upon by employees. The company applies lean tools like pull production, quality at the source, and 5S, but faces challenges with just-in-time (JIT) management and equipment efficiency, especially in reducing inventory at reworkable material stores. The study found that a well-implemented pull system helps prevent overproduction, but the frequent waste of waiting is not solely due to poor pull system implementation. Equipment inefficiency and large reworkable inventories were also not directly caused by a lack of JIT. Ultimately, longer waiting times increase manufacturing costs, underscoring why reducing lean wastes is vital for cost reduction.

A. Siddiqui [33] reviewed 18 papers and quality management websites, finding unanimous agreement on the use of 5S and 7 Muda methods for improving health care systems globally. These methodologies are effective for initiating, managing, and sustaining improvements in struggling health systems across various countries.
Ethiopia is investing in manufacturing to achieve lower-middle-income status by 2025, focusing on increasing productivity, quality, and competitiveness in export-oriented industries. Over the past eight years, Ethiopian manufacturers had worked to enhance productivity and efficiency. The Kaizen approach—centered on continuous improvement—plays a key role in this transformation, helping to restructure industries and drive development. Kaizen is believed to significantly improve manufacturing efficiency, as supported by Structural Equation Model (SEM) analysis.

A. Abebe [34] also showed that the company culture of Kaizen 5S (housekeeping), waste (Muda) eliminations, and PDCA cycle philosophy as a continuous improvement program positively and significantly affects productivity. In addition to the step-by-step approach, Kaizen approaches implemented together may boost productivity. PDCA analysis mediates the huge productivity boost Kaizen 5S (housekeeping) implementation procedures provide, according to SEM bootstrapping. Continuous manufacturing process improvement through scientific problem solving through PDCA adoption considerably mediates the association between 5S (housekeeping) and productivity improvements.

The Extended Value Stream Mapping (Extended VSM) framework by M. Sahdhani et al. [35] integrated ergonomic and cognitive assessments to better identify the eight categories of waste in lean manufacturing. The Extended VSM integrated Stopwatch Time Study (STS), Rapid Entire Body Assessment (REBA), and NASA-TLX to map operational and human-centered wastes, including overproduction, waiting, transportation, overprocessing, inventory, motion, defects, and unutilized talent. Extended VSM gives multidimensional diagnostics by combining regular VSM symbols with ergonomic risk assessments, mental workload indications, and intuitive icons. This strategy improves efficiency and worker well-being, making it valuable for labor-intensive manufacturing facilities seeking sustained lean transformation.

F. Wicitra et al. [36], The Waste Assessment Model (WAM) calculation revealed that the largest waste in animal feed production was waste defects (29.20%), waste inventory (19.63%), and waste motion (13.20%). The biggest waste category was faulty. The investigation demonstrated that the primary categories of waste in animal feed production affect each other. The Waste Relationship Matrix (WRM) and Waste Assessment Questionnaire (WAQ) studies showed that defect waste affects inventory and motion waste. If defective items rise, inventory and motion waste may too. This suggested that partially improving one waste category without addressing its link with other wastes may cause new production system inefficiencies. To maximize manufacturing process efficiency, a comprehensive and integrated improvement approach must consider waste interrelationships. The improvement technique reduced production Leadtime to 6 minutes 13 seconds, improving efficiency.

K. Hys et al. [37] studies of the investigated workstation found that implementing rationalization at the semi-automatic workstation increased working time by 114 minutes each month. The monthly tooling changeover is based on customer demand. As per the annual production schedule, a semi-automatic workstation with a robotic pallet system is now available for 1368 min/year, or 22.8 hours/year. the annual time change when the investigated semi-automatic workstation is halted to change tooling for following manufactured goods before and after rationalizations.

According to T. Redha et al. [38], the distribution process from Line 1 Warehouse (PT. PIM) to Line 3 Warehouse (Lhokseumawe) was as follows: The waste detection results showed overprocessing and unnecessary movement. The warehouse truck inspection process was wasteful in the Over Processing area. Implementing a monitoring board was suggested. Fertilizer pickers and truck loading caused waste in the Unnecessary Movement category. An additional worker to arrange fertilizer was suggested. Goods at Line 3 Warehouse unloading area. The Line 3 Warehouse unloading area would benefit from a conveyor belt to speed up placement. Arena Simulation found that Scenario 6 reduced waste by 36.49% when Lean Distribution was implemented for urea fertilizer products. Optimization of activities 20 and 6 yielded the optimum Lean Distribution scenario. Thus, processing time dropped from 343 to 323 minutes, saving 20 minutes.

D. Shedge et al. [39] aimed to kill all three Lean enemies, but it may not be possible. Unless your factory was near your customer, Muda will require transportation. Similar for Muri. Sometimes machines or people need to work harder or take longer to fulfil a customer request. Finally, Mura rarely decreases 100%. When making different products, they would need different materials, methods, or cycle times.

J. Zvidzayi [40] found that Gemba Kaizen improvements at Toyota South Africa (TSAM) and its suppliers streamlined processes, improved quality, reduced material use, and increased employee satisfaction. Success in lean management was linked to employee happiness and a willingness to improve. Gemba walks were conducted with respect and a focus on observation and feedback, not criticism or enforcement, to encourage openness and continuous improvement. Former TSAM employees often became Gemba or Kaizen leaders at supplier companies, with staff rotations primarily for senior management advancement rather than layoffs. Key drivers of Gemba Kaizen success included teamwork, quality planning, employee training, management support, clear goals, team autonomy, and experience—all contributing to higher productivity.

2.4. Root Cause Analysis

Root Cause Analysis (RCA) is a systematic process aimed at identifying the root causes of problems to prevent future occurrences. It involves five steps: defining problems, collecting data, analysing data, identifying root causes, and determining corrective actions. Various methods for RCA include Fishbone Diagrams, Pareto Analysis, 5Whys, Brainstorming, Failure Mode Effect Analysis (FMEA), and Six Sigma. Fishbone Diagrams, for instance, categorize potential causes into 4M and 1E factors (Man, Method, Machine, Materials, Environment) and can improve product quality and eliminate non-conformance issues. However, they primarily utilize qualitative data and may struggle with complex analyses. RCA has revealed key issues in a specific company, such as inefficient decision-making stemming from poor management understanding of data, excessive and poorly grouped information, and inadequate software for data presentation. To enhance decision-making effectiveness, the integration of divisions and a dashboard for relevant data display is recommended. [41]

G. Singh et al. [42] showed that the use of flange fixtures in plunger bush bore machining reduced vibrations and enables higher machining parameters. Flange fixtures were an economical solution to the overhang problem of big cylindrical works during drilling when stable rest cannot be used owing to diameter or cost. Other industries making similar jobs would benefit from this fixture.

K. Ghatorha et al. [43] found that in towel tissue production, the main types of waste were critical waste (20.31%), overproduction (18.59%), motion (15.30%), inventory (14.94%), transportation (13.80%), waiting (8.99%), and process waste (8.08%), as identified through observations, interviews, and Waste Assessment Model (WAM) analysis. Root Cause Analysis (RCA) revealed that defects, overproduction, and motion were caused by issues such as Yankee scale buildup, clogged showers, human error, management rules, low operator awareness, manual transfer, and insufficient facilities. The 5W1H method was used to recommend solutions like maintenance SOPs, FIFO systems, and improved tools. Emphasizing the use of digital technology, the study's improvements—informed by Future Value Stream Mapping (VSM)—reduced total lead time, lowered Non-Value Added (NVA) activities substantially, and raised Process Cycle Efficiency (PCE) from 45.26% to 64.38%, a 19.12% increase.

S. Sarkar et al. [44] Noted that Lean Six Sigma RCA could be used for both regular and rare nonconformities or faults. RCA with hypothesis test could be used for frequent non-conformities or defects alone. However, this technique depended on how the team narrows the search area of likely causes to manageable numbers. The nature of problem determined the search space reduction methods such stratification analysis, branch-and-prune approaches. This topic had considerable potential for investigation. Future study could focus on RCA for rare nonconformities, such as deadly accidents in plants, incorrect patient treatment in healthcare, and plant shutdowns.

B. Vo [45] found that using Industry 4.0 technologies for root cause problem solving leads to more efficient and effective issue detection in manufacturing. By integrating nine elements—including big data analytics, autonomous robots, simulation, system integration, IIoT, cybersecurity, cloud, additive manufacturing, and augmented reality—defect recurrence can be prevented. In a real manufacturing case study, technology management practitioners were shown how to apply these tools, successfully identifying and addressing the root cause of defects, which resulted in fewer customer complaints and failures. The implemented design solutions improved actuator components to meet technical requirements, raising the capability index (Cpk) from 0.59 to 1.98. This improvement led to a significant drop in customer complaints. The study suggests that companies adopting root cause analysis with Industry 4.0 tools can achieve superior customer service and enter a new era of technological advancement.

D. Guzel et al. [46]found that SMEs can boost efficiency by applying lean production techniques, as demonstrated by the couch manufacturing company. The couch production plant established a value stream mapping and previous data monitoring system to analyse the current condition. Lean manufacturing was used in bottleneck activities (Frame, Paint, Sewing, Upholstery) on the most sold product. Time was saved and mistakes were avoided. Next, work was separated into small lots to ensure lean production and one-piece flow. The one-piece flow application reduced waiting times by 65%. The implementation of lean production processes led to a 29% improvement in annual labor times. Limitations of the research include difficulty in collecting accurate employee data and employee resistance to change. Not all lean manufacturing strategies were applied.

M. Yanti et al. [47] focused on door frame production due to high monthly demand. Using Current Value Stream Mapping, they identified wastes such as defects, waiting, overprocessing, and motion. A fishbone diagram helped trace the root causes. To reduce waste, they recommended equipment inspections, maintenance report cards, method sheets, and production control cards. After implementing Lean manufacturing improvements, Future Value Stream Mapping showed that lead time dropped from 2,490 to 1,959 and process efficiency increased from 69.40% to 88.20%. These changes made production more efficient, helping to meet targets and customer demand.

S. Holifahtusn Sakdiyah et al. [41], Organizational decision-making required qualified management, including the appropriate decision-maker. Second, properly processed data was accurate, timely, and relevant. Third, company news must be shared throughout departments. When the decision-making process was qualified, the company's management's problem-solving decisions would be correct. Analysis employing RCA and fishbone diagrams reveals decision-making issues in detail. Each problem in the fishbone diagram can be solved to make informed decisions that address the company's primary challenges.

H. Oktariani et al. [48] found that the RSAU lab faced six out of seven types of waste—excluding inventory waste—with overprocessing (mainly repeated blood sample collection) being the most significant at 19.8%. Patients reported inefficiencies, especially during registration and waiting for lab result sign-off. Using Root Cause Analysis, the study prioritized overprocessing for improvement. As a result, Process Cycle Efficiency (PCE) rose from 41% to 74% at registration and from 33% to 68% at sign-off, indicating much more efficient lab processes.

W. Sulistiyowati et al. [49] found that the most valuable waste was a fault of 16,3. The fundamental reason of the high waste defect was human and machine factors because they didn't comprehend the flat glass production process adjusted to the company's SOP.

P. Gangidi [50], extended 3×5 Why's can help organizations find actionable root reasons for solving challenges. Separating a problem statement into occurrence-specific, human, and system components and completing 5 Whys on each will reveal underlying concerns. Organizations benefit most financially from uncovering these underlying 5 Whys. A risky dozen-based human deviation form must be established and used actively to monitor and prevent human errors in businesses.

2.5.Just In Time (JIT)

JIT manufacturing stresses a push-through method, starting production only after consumer orders, reducing inventory and waste (Pinto et al., 2020). Downstream JIT matches production to client demand to avoid delays and overproduction, while upstream JIT assures suppliers meet needs with small batch sizes. Correct customer orders and fast supplier deliveries are essential for JIT (Schonberger & Brown, 2017). Halim et al. (2015) used regression analysis to examine the correlations between JIT time, enterprise costs, delivery time, and quality. JIT aims to reduce inventory. [51]

S. Biwott et al. [52] found that just in time affected cement manufacturing firm performance statistically. Just-in-time inventory boosts Kenyan cement manufacturers. Resource-based theory supported these findings. Cement manufacturers can maximize output by strategically using JIT resource procurement. Therefore, cement manufacturers should gather and analyze important data to support inventory management decisions. Less movement on the shop floor lets teams focus on developing superior products. To reduce waste and exceed consumer expectations, supply chain activities should run smoothly. Investments in equipment and processes should enable quick changeovers and efficient small-batch production.

L. Keating [53] found that combining Lean Manufacturing with sustainable and digital technologies can significantly enhance operational excellence and long-term profitability in the U.S. apparel industry. Lean principles like waste reduction, process efficiency, and maximizing value, when integrated with eco-friendly and digital innovations, improve manufacturing performance and financial outcomes through better cycle time, lead time, and OEE. Sustainability-driven Lean systems also foster ongoing improvement, innovation, and environmental responsibility, aided by technologies such as AI analytics, IoT monitoring, and renewable energy systems, which increase resource efficiency and strengthen brand reputation.

The study highlighted challenges such as skill gaps, resistance to change, and the ongoing need for digital training, emphasizing that strong management commitment and government support are essential for successful green production. Ultimately, integrating Lean with sustainable and digital practices can balance profitability, ethics, and environmental goals, positioning Lean as a strategic framework for lasting value and growth in the fashion industry.

A. Chijioke et al. [54] examined process cycle efficiency to improve surfactant production. We examined VDT, NVDT, and lead times before (Tb) and after (Ta) optimization. The study analysed non-value-added times (NVD, Tb, Ta) and labor hours (Lb, La) before and after optimization utilizing lean manufacturing approaches. We assessed waste productivity using process cycle efficiency. In 2017, a surfactant production firm analysed its VDT and NVDT to compare efficiency before and after optimization. The Just-in-Time methodology was used to improve the surfactant production process. After improvement, take time fell greatly while increasing exponentially. Last, the manufacturing volume rate was determined using the Just-in-Time approach.

S. Prasanna et al. [55] demonstrated that lean manufacturing is essential for modern production, helping companies increase efficiency, streamline processes, and minimize waste. Techniques like 5S, JIT, Kaizen, VSM, and TPM improve operations, profitability, product quality, customer satisfaction, and staff involvement. The research concluded that adopting lean manufacturing as a long-term strategy leads to sustained corporate success and competitive advantage, even in the face of resistance to change. As industries continue to evolve, lean manufacturing remains crucial for enhancing operational efficiency and profitability.

2.6.Key Performance Index (KPI)

KPIs are a series of activities that require time and resources to meet assessment standards or principles, which are used to measure and evaluate performance, and the methods of measuring project success over time have been developed. Initially, project success is assessed based on its duration and performance, followed by the “iron triangle” of cost, quality, and time. [56]

A. Gomaa [57] evaluated TPM and VSM integration to improve efficiency, waste reduction, and equipment reliability. TPM improves equipment performance by coordinating maintenance and production, whereas VSM reduces material and information flow inefficiencies. A systematic TPM-VSM methodology for manufacturing excellence results from their integration. This research on an Egyptian spare parts manufacturer's machining process built a comprehensive TPM framework using advanced analysis and improvement methods. In three months, TEEP rose from 58% to 68%, OEE from 65% to 76%, and value-added process efficiency from 37% to 54%. These findings improve equipment use and maintenance techniques for operations management.

H. Hatif et al. [51] found that implementing lean manufacturing strategies in the textile industry led to significant improvements in employee performance and workplace efficiency. At Ulfaz Collection, adopting lean methods like Just-in-Time and flexible production increased productivity, reduced lead times, and improved responsiveness to market demands, resulting in higher customer satisfaction and competitiveness. The study highlighted that committed leadership and active employee participation are crucial for successful lean implementation, and continuous improvement is necessary to maintain its benefits. Overall, lean manufacturing enhances efficiency, productivity, and competitiveness through waste reduction and greater staff engagement.

Z. Shreif et al. [58] created a framework to select environmental KPIs for the manufacturing industry, acknowledging that sustainable practices can boost profits and reduce environmental impact. They compiled and categorized KPIs from literature, developed a ranking method based on selection criteria, and validated the framework through expert surveys and a case study. The framework proved effective in organizing and analyzing KPIs, highlighting neglected areas, and aiding in the informed selection of KPIs, thereby enhancing decision-making for environmental sustainability in manufacturing.

A. Bigwanto et al. [59] found that using phase-specific KPIs is crucial for evaluating lean construction success and identifying performance challenges. These KPIs help uncover obstacles, inform lessons learned, and lead to the creation of Standard Operating Procedures (SOPs) for future projects, supporting sustainability and long-term organizational benefits. The indicators were customized for each project phase—initiation, design, implementation, and closure—and accounted for factors like geography, project complexity, and organization size, especially during implementation. The study established lean construction KPIs for building projects and adapted the model for various delivery systems, such as Design Bid Build (DBB) and Integrated Project Delivery (IPD), by including relevant processes in the indicators.

B. Lyna et al. [60] highlighted that Green Lean Six Sigma (GLSS) can transform sustainable manufacturing by combining Lean Six Sigma with environmental initiatives to boost efficiency and reduce environmental impact. Successful GLSS implementation depends on strong leadership, employee engagement, suitable technology, and the use of sustainability KPIs across environmental, economic, and social dimensions. Despite challenges, case studies show GLSS is effective in diverse environments. Integrating Industry 4.0 technologies, such as IoT and Cyber-Physical Systems, further enhances GLSS by supporting real-time, data-driven improvements. Overall, GLSS and advanced technologies can greatly increase sustainability and efficiency, positioning companies as leaders in sustainable manufacturing. The study recommends future research to improve measurement methods and expand GLSS to more industries.

R. Alramli [61]examined industrial company measurements and KPIs to improve operations and answer questions. It emphasized that company and departmental needs determine KPI selection and that better communication was needed for implementation. Language hurdles and data shortages shifted the research to theoretical rather than practical ways. Current KPIs, management structures, and digital transformation implications were covered. It found that technical proficiency requires training and suggests a bottom-up leadership model with KRA metrics for lasting solutions. Organizational systems and KPI-KRA integration need more investigation.

M. Azad [9] found that implementing lean manufacturing tools like 5S, Kaizen, JIT, and VSM in textile mills led to significant improvements—including reduced production costs, fewer defects, shorter lead times, and better inventory turnover—without requiring major investments. Lean practices eliminated waste and streamlined workflows, cutting costs by 20% and lead times by 30%, even in resource-constrained environments. Success relied on employee involvement and management support. The study also suggested that integrating digital technologies (Lean 4.0) such as AI and IoT could further boost efficiency. However, research was limited to a few mills, so broader studies are needed for wider application and to assess the long-term sustainability of lean improvements. Overall, lean manufacturing, strengthened by staff engagement and digital tools, can greatly enhance efficiency and competitiveness in the textile industry.

Here's a concise summary preserving the original meaning:
A. Bumba [62] demonstrated that a KPI tree structure, which organizes performance indicators hierarchically, helps management make decisions by clarifying the relationships among KPIs and enabling concise monitoring of value streams. However, widespread use is limited by inadequate data collection systems. KPI trees require collecting and comparing KPIs and targets to identify improvement areas and the causes of deviations, but do not offer direct solutions. Effective use depends on establishing mathematical and logical connections among indicators and standardizing measurement and analysis processes. In a case study, a productivity KPI tree successfully linked dependent and independent indicators, improving performance tracking.
The study also found that training aimed at improving employees' knowledge, skills, and attitudes is crucial. Motivation, driven by factors like salary, working conditions, growth opportunities, fairness, recognition, and community, boosts employee engagement, which in turn enhances behavior and performance. Organizational efficiency is measured using internal productivity KPIs, which now consider not only labor and materials but also capital, energy, efficiency, quality, and customer satisfaction.

S. Alyahya et al. [63] investigated what influences employees' perceptions and knowledge of KPIs in Saudi paint manufacturing plants. Their study, grounded in literature review and supported by correlation and regression analyses, found that employee training, engagement, and motivation all have significant positive impacts on KPIs. Specifically, training ($r = 0.574$), engagement ($r = 0.597$), and motivation ($r = 0.628$) were all strongly and significantly correlated with better KPI performance. Regression analysis showed that these factors together explain 48.1% of the variation in KPIs. Each factor—training, engagement, and motivation—had positive regression coefficients, indicating that improvements in these areas enhance KPI outcomes.

A. Heydarzade et al. [64] introduced the MLMV-VSM framework to address the challenges posed by Industry 4.0 technologies—such as IoT, digital twins, and big data analytics—that have increased the complexity and interconnectedness of manufacturing systems. Unlike traditional, static VSM methods focused only on operational data, the MLMV-VSM framework integrates operational, environmental, and social factors, capturing KPI interdependencies across these areas. By including human-centric indicators, it optimizes technical performance, environmental sustainability, and worker well-being. This comprehensive approach makes MLMV-VSM a vital tool for aligning production processes with stakeholder value and sustainability in the context of Industry 4.0.

A. Petteri Pelto [65] studied how to balance and select effective KPIs for internal logistics at BRP Finland Oy by combining literature review with company interviews. The research used content analysis and a scoring matrix to evaluate KPIs based on their relevance, measurability, diagnostic value, controllability, and strategic alignment. Many existing KPIs were found to be unsuitable, so new ones were validated with stakeholders and aligned with the balanced scorecard framework. The selected 14 KPIs, covering Productivity, Quality, Finance, People, and Health and Safety, provide a comprehensive overview and support both operational and strategic objectives, avoiding partial optimization. The study highlights the importance of regularly updating KPIs to reflect evolving strategies and stresses that successful performance measurement requires integrating theory, operational knowledge, and stakeholder input.

H. Kurnia et al. [66] found that the main sources of defects in production were machine issues (misaligned needles, thread clumps in the cutter), material variability (yarn hardness), and procedural problems (socks moving directly to the plate). The highest risk priority numbers (RPN) were linked to unsuitable linking needles (504), variation in yarn hardness (441), cutter thread clumps (384), and socks entering the plate directly (294). After implementing improvements—such as using new needles, standardizing yarn hardness, improved cutter timing and cleaning schedules, and thorough checks—sigma levels increased by 7% (from 3.7017 to 3.9614), and defect rates dropped by 11.08% before and 5.54% after improvements. The study suggested integrating lean methods for greater efficiency and recommends including sigma as a KPI in the knitting department to support continuous improvement.

V. Swarnakar et al. [67] addressed the sustainability challenges of automotive component manufacturers, who use significant resources and generate pollution. The study developed and assessed key performance indicators (KPIs) for sustainability based on the triple bottom line (3BL) approach. After identifying 23 initial KPIs from the literature and validating them with industry experts, the researchers finalized 18 KPIs across three sustainability dimensions. Using the Analytical Hierarchy Process (AHP), experts assigned importance weights to these KPIs and evaluated five automotive component manufacturers. The results showed that a company's overall performance score does not always reflect its lowest sustainability factor, highlighting the need for targeted improvements. The study encouraged plant managers to take actions to boost sustainability performance and provided a model for practitioners, decision-makers, and researchers to evaluate organizational sustainability in the industry.

Jain & Kachru [68] showed that integrating Enterprise Asset Management (EAM) with fuzzy AHP-TOPSIS/RADAR methods enables SMEs to effectively prioritize KPIs for performance management. Their cloud-based platform facilitated KPI selection, ranking, data collection, and analysis, making advanced performance management accessible to resource-limited firms. The study introduced an EAM-MCDM KPI prioritization model and a fuzzy RADAR method, using various TOPSIS and RADAR approaches to rank KPIs and support sustainable production and resource optimization. Academic-industry collaboration was found valuable for decision-making and continuous improvement. The proposed process, which uses SMARTER criteria, fuzzy AHP, and TOPSIS, helps SMEs identify performance measures aligned with environmental and socio-economic goals. Future research will further refine the fuzzy RADAR method. Overall, this approach promotes KPI-driven decision-making for sustainable industrial development and greater operational efficiency.

B. Kassem et al. [69] addressed skepticism about the practicality of lean monitoring by demonstrating the effectiveness of lean frameworks in their case study. Applying lean concepts significantly reduced lead time, and the A3 problem-solving method helped address issues comprehensively. The successful implementation encouraged the company to adopt this approach for future projects, with positive feedback from both staff and management. Introducing a digital KPI dashboard further streamlined operations by reducing non-value-added activities. The study showcased how Lean, supported by simple digital tools, can improve processes and customer relationships, and aimed to guide managers in adopting Lean practices effectively.

2.7. Kaizen

There is always room for process improvement. Kaizen, a lean thinking tool, improves safety, productivity, quality, and workplace culture. It increases profitability, stakeholder relations, and client happiness in construction organizations, boosting project growth. Kaizen also improves service and staff work experiences in hospitality and tourist management. Continuous improvement optimizes processes and practices for accuracy, efficiency, and effectiveness. [70]

I. Tone et al. [71] showed that using the KAIZEN method and related tools effectively addressed production issues, increased efficiency, and raised Jobs Per Hour (JPH), making cycle time unaffected by paint repairs. The approach eliminated wastes like overprocessing, inefficient movement, excess inventory, quality defects, and unnecessary costs such as extra materials and overtime. Continuous improvement through KAIZEN targeted all forms of waste, including the traditional seven Lean wastes and an eighth: underutilized human potential. Overall, Lean manufacturing and KAIZEN enhanced factory efficiency, shortened cycle times, improved quality and customer satisfaction, and removed the need for corrective actions.

M. Patel et al. [72] presented a case study on the effects of kaizen on an injection moulding machine. Waste reduction, tool organization, and process standardization were prioritized. Kaizen is a common term in this competitive business. It entails persistently finding and fixing issues. Kaizen concepts improve process and personnel performance with minimum investment. Kaizen and innovation are needed for company growth. Innovating requires a lot of money. Kaizen improves current systems with less capital. No revolutionary inventions are needed to apply kaizen; only common sense and process understanding are.

S. Kumar et al. [73] found that implementing Kaizen events, along with electronic information and kanban systems, effectively reduced inventory in a selected SME. Analysis of data before and after adopting Lean-Kaizen and VSM showed lower rejection and rework rates, higher productivity, and improved SKS product quality. Kaizen improvements carried out over 20 days led to significant process benefits: clamping/de-clamping time dropped by 51.72%, hourly production at P5 increased by 47%, manpower needs halved, production lead time was reduced by 69.54%, value-added time was cut by 75.25%, and production flow and working conditions improved.

S. Kumar et al. [74] showed that Indian SMEs still lack lean awareness and missed out on many benefits. Few successful lean implementation studies in Indian organizations were published. This case study used value stream mapping to execute Lean-Kaizen to eliminate inefficiencies and wastes in the selected company's processes. The report outlined a waste management plan. Case study resulted from Indian manufacturing showed how to detect and eliminate waste. The study found that machine setting time was reduced by 65.85%, manpower by 40%, production lead time by 69.47%, and value-added time by 75.25%, improving production and industry conditions. The case study can assist managers and practitioners discover waste in their organization's processes.

O. Ortiz [75] concluded that the Kaizen approach significantly influences productivity, occupational health and safety, workplace environment, and organizational philosophy. Reviewing 50 relevant papers, the study found that Kaizen promotes field self-discipline: 40% of the papers addressed misconceptions about Kaizen in manufacturing, 32% focused on Lean culture and Kaizen's industrial importance, and 28% discussed its implementation across various sectors, including healthcare and telecommunications as well as industry.

B. Mwenda et al. [76] studied the impact of Kaizen on manufacturing, finding that continuous improvement is essential for competitiveness. Their case study reduced defects from 4% to 2%, meeting the target set before Kaizen was introduced. The project demonstrated that Kaizen tools and teamwork can drive lasting change, even though only one type of defect was addressed within a limited timeframe. The approach can be expanded to other production issues for broader improvement. Establishing a Kaizen culture involves encouraging staff to be patient and focus on long-term gains. While immediate results were limited at Kilimanjaro International Leather Company, benefits are expected to emerge over time. Kaizen consultants supported the company throughout, equipping employees to apply Kaizen methods after the project's completion.

S. Vierci-Codas et al. [77] improved the fresh and frozen product (FFP) process at a Paraguayan retail distribution center using Lean Manufacturing (LM) methods. Their literature review highlighted a lack of LM research in retail for emerging markets, guiding the selection of effective lean tools for Latin America. Techniques like flow charts, brainstorming, Ishikawa and Pareto diagrams, and VSM were used to analyze the FFP process. The study identified four main challenges, with 56% tied to labor, methods, and environmental factors, which hindered efficiency and delivery times. Non-value-adding steps, such as product storage and regularization, were identified, while the reception and dispatch stages were most valuable. Eliminating the regularization sub-step through VSM led to a 96% process improvement. Kaizen methods, including 5S and the PDCA cycle, supported ongoing improvements. Overall, applying LM tools to logistics and distribution reduced waste and enhanced competitiveness.

A. Dhingra et al. [78] found that while SMEs face many daily operational challenges, few studies guide them toward lean solutions. Their research used Lean-Kaizen and value stream mapping to identify and address quality issues in a selected organization. Lean implementation reduced waste, variability, and cycle time, improved customer satisfaction, and achieved zero defects. One Kaizen event alone cut rejection costs by 1250 INR per day (0.45 million INR a year). The study highlighted that Lean-Kaizen not only lowered costs and improved quality but also faced challenges in encouraging employees to share knowledge. On-the-job training led to notable productivity and quality gains. Overall, Lean-Kaizen addressed real quality concerns for Indian SMEs, promoted continuous improvement, and offered practical strategies for managers, researchers, and decision-makers to enhance industry quality and efficiency.

J. Medina et al. [79] successfully reduced waste in the bandage rolling machine by matching machine and operator speed, minimizing stoppages and waste. The approach, which included detailed diagnosis of the "Bandage Area" and application of Kaizen methodology, led to cost savings, shorter waiting and cycle times, and higher quality. A preventive maintenance system based on maintenance orders was introduced to prevent breakdowns and further reduce waste. These strategies will be applied to other bandage winding machines for improved results. Overall, the project allowed the company to expand output, lower costs, and enhance product quality by combining speed adjustments, Kaizen practices, and preventive maintenance.

E. Vargas Crisóstomo et al. [2] showed that before using Lean Manufacturing, a baseline or diagnostic 5S study yielded an average value of 2.8. After applying 5S, the aqueous adhesives manufacturing area was organized and cleaned, saving time looking for materials and moving staff, resulting in an average audit score of 4.03. Kaizen lowered the manufacturing process time of the highest-selling aqueous adhesives product. Kaizen cut manufacturing time from 20:15 to 17:09 hours. Lean Manufacturing can boost productivity, revenue, profitability, customer happiness, staff satisfaction, and work environment in the manufacturing organization under consideration.

B. Vo [45]showed that with the implementation of Lean principles, Kaizen events were becoming more popular in enterprises. Kaizen improves routine daily activities and procedures to eliminate waste in all company systems, either incrementally or long-term, resulting in considerable streamlining or financial advantage. Kaizen events aimed to get every employee to spot issues, find the source of system waste and inefficiency, and improve the workplace.

P. Kumar et al. [80] demonstrated that the Kaizen tool is an effective Lean manufacturing strategy for addressing organizational problems, achieving an annual cost saving of $535.20 and eliminating rejections in wire harness production. The study emphasized monitoring production and DOL stages to prevent recurring issues and highlighted Kaizen's ability to reduce plastic lock rejections. Encouraging employees to participate in quality circles and ongoing training is crucial for fostering continuous improvement and better communication between workers and management. Although Kaizen is widely used in Indian organizations and applicable across various industries, there remains potential for broader implementation, especially among shop floor workers who have valuable operational knowledge. Management support and employee training are essential for realizing organizational goals through Kaizen.

A Kaizen training program conducted in several Ghanaian manufacturing companies from 2012 to 2017 was evaluated using the DID methodology to assess its impact on productivity and performance. R. Atta-Ankomah et al. [81] found that the program generally improved business performance, providing empirical evidence of Kaizen's positive influence in Ghana and showing its applicability in less developed countries. The study introduced two new insights: the impact of Kaizen depends on company size and the quality of the training consultant. While previous research has explored factors affecting Kaizen's success, further study is needed to understand these effects across different company sizes and consultant types in Ghana. The findings suggest that expanding Kaizen training could significantly support Ghana's industrial development, but training should be tailored to the needs of organizations of varying sizes.

N. Verma et al. [82] found that their questionnaire was highly reliable (Cronbach Alpha > 0.8) and that within-group co-variance was appropriately higher than between groups. Strong correlations were observed among customer relationships, innovation challenges, skilled labor and advanced machinery, and supplier development. Key success factors identified included management commitment, work environment, Kaizen enablers, skilled labor, up-to-date machinery, and the role of innovation. Statistical analysis showed significant performance improvements, especially in later project phases. Overall, the study concluded that Kaizen delivers benefits in any workplace.

C. Okpala et al. [83] concluded that applying Kaizen concepts in industrial processes greatly enhances efficiency, quality, and employee engagement. Continuous improvement and employee empowerment provide organizations with sustainable competitive advantages. Tools like Kaizen events, 5S, and JIT help manufacturing firms achieve operational excellence and improve customer satisfaction. Case studies confirmed that Kaizen is vital for ongoing improvement and long-term performance, fostering a culture where every employee contributes to company growth and sustained success.

P. Walentynowicz [84] found that while many articles endorse Kaizen and stress the need for a supportive organizational culture, few—especially Polish studies—detail how to achieve such a transformation. The article aimed to develop and propose a practical methodology for creating a Kaizen-oriented culture in industry, based on empirical research. Unlike other models, such as "course correction" or Lean cultural change, this new approach specifically targets cultural transformation toward Kaizen. The proposed strategies and model fill an important gap and can help managers understand and cultivate a Kaizen culture within their organizations, though the process is lengthy and can take years to fully implement.

N. Verma et al. [85] showed that Kaizen was frequently used in production, thus further research was needed. The researchers thought Kaizen might be used in homes, businesses, and industries. Kaizen reduced MURA, 3M-MUDA, and MURI, which cause inconsistency, annoyance, and waste. It boosted supplier-customer interactions and on-time delivery. Kaizen can also be utilized alongside TQM, TPM, JIT, and 5S to improve performance and compete in a market. Kaizen and top management were affected by software and hardware enablers. Kaizen relies heavily on employee awareness. Thus, further research is needed to improve this and help top management apply Kaizen in specific sectors. Additionally, future studies can determine which businesses are suitable for this technology. Also, Kaizen implementation hurdles can be researched.

E. Laksanawati et al. [86] found that successful Kaizen Men understand lean tools and procedures and have excellent communication and leadership abilities that promote cooperation and continual improvement. Textile and garment manufacture presented distinct challenges that require problem-solving and innovation. The research also underlined the necessity for specific training and development programs to develop essential capabilities and corporate commitment to continual worker development. By investing in Kaizen Men's skill development, organizations might enhance operational performance, adapt to changing market conditions, and achieve long-term success.

B. GAJDZIK [87]showed that the broad knowledge offered about Kaizen in Smart Manufacturing projects could help plan and develop adjustments that start at individual workstations or machines and end up in Smart Manufacturing. Each endeavor had a purpose. According to Kaizen, staff should be involved in planning and improvement initiatives at workstations and given the initiative to execute improvements, especially when enhancing control workstations. Kaizen and Smart Production can coexist in Industry 4.0, especially when organizations transition to smart manufacturing. A highly digitalized organization could employ smart Kaizen based on digital twins and other Industry 4.0 technologies and pillars.

N. Sundararajan et al. [88] demonstrated that long-term planning—such as major changes in plant layout, workflow, equipment upgrades, and automation—leads to sustained, high-quality results in industrial settings, aligning with management’s vision. Software simulations of collected data provided valuable insights for identifying problem areas and understanding factors affecting workplace efficiency. In the short term, adding cutting operators improved productivity by 10% without significant cost. For lasting impact, the study recommended quality control systems and effective workplace organization and maintenance, which increased worker involvement and ownership, resulting in a 116% productivity gain over the long term.

M. Syaputra et al. [89]showed that Kaizen can handle qualitative and quantitative data challenges. Kaizen can enhance work system quality, energy usage, lead time, performance, etc. Kaizen has been used in manufacturing, logistics, construction, SME, service, healthcare, pharmaceutical, and continuous improvement operations. The kaizen method appears to be effective in improving systems in all sorts of organizational institutions.

N. Agustina [90] thoroughly examined Kaizen's key role in improving manufacturing processes. The research found that Kaizen enhances productivity and quality through continuous improvement, employee involvement, and systematic problem-solving. Successful implementation relies on strong management commitment, effective training, and a culture open to change. Challenges such as employee resistance, inadequate training, and sustaining continuous improvement were noted, but could be overcome with strategic planning and leadership support. Overall, the study showed that Kaizen can transform factory performance, fostering a culture of excellence and innovation for long-term manufacturing success when properly applied.

A. Dahiya et al. [91] demonstrated that applying lean principles in the automotive sector increased HLLS assembly line productivity. The study confirmed that lean manufacturing improves efficiency, productivity, quality, and overall organizational performance, suggesting that these methods can help other assembly lines meet future demand and stay competitive globally. Key results included a 28.57% reduction in PCB soldering cycle time and a 3.88% decrease in product throughput time. Improvements extended to enhanced 5S practices, higher morale, better understanding of lean techniques, and energy savings. The research focused on productivity gains using Kaizen and 5S tools, emphasizing the importance of a cross-functional management framework to maximize benefits. Integrating lean components like JIT and TPM with process improvements can further boost production and quality.

2.8. Value Stream Mapping (VSM):

Value Stream Mapping (VSM) is a lean manufacturing tool designed to pinpoint and eliminate non-value-added activities in production processes, analyzing the flow of materials and information to enhance efficiency. VSM serves as a continuous improvement mechanism, mapping both current and potential future states of production to identify waste, reduce lead times, and improve cycle times. Numerous studies have demonstrated VSM's effectiveness across various sectors, achieving significant gains such as a 92% reduction in lead time and a 90% decrease in work in progress (WIP) in the furniture industry, as well as a 30% reduction in cycle time in bonnet manufacturing. Despite its successful applications elsewhere, research on VSM's effectiveness in Tanzania, particularly within the agricultural value chain, remains scarce, highlighting a critical gap where VSM could substantially improve production operations, particularly in rice milling.[92]

D. Guzel et al. [46] showed that lean production strategies in SMEs can boost productivity, as demonstrated by the implementation of these techniques in a couch manufacturing company. The couch production plant established a value stream mapping and previous data monitoring system to analyze the current condition. Lean manufacturing was used in bottleneck activities (Frame, Paint, Sewing, Upholstery) on the most sold product. Time was saved and mistakes were avoided. Next, work was separated into small lots to ensure lean production and one-piece flow. The one-piece flow application reduced waiting times by 65%. The implementation of lean production processes led to a 29% improvement in annual labor times. Employee resistance to change and data gathering issues hinder the research. Not all lean manufacturing strategies were applied in this study.

A. Eesa [93] found that revising the value flow map significantly improved process efficiency and reduced waste. In the current state, adding value took 50.5 minutes, while the proposed future map reduced this to 23.5 minutes. Non-value-added time was also cut from 310.5 minutes to 96.5 minutes, achieving waste reductions of 53.5% (value-added activities) and 69% (non-value-added activities). Service efficiency improved from 14% to 20%. Key improvements included opening more ticket outlets, prioritizing patients, speeding up registration and scheduling, enhancing nurse efficiency, fixing and upgrading lab devices, adding drug suppliers, and streamlining administrative tasks. Overall, the cycle time dropped from 21 minutes to 15.5 minutes (a 26% reduction), making the operation more efficient.

M. Al-Farabi et al. [94] found that, before improvement, the Rear Door Service Hole Cover BZ 460 RH production process had a lead time of 139.44 seconds per unit and a process cycle efficiency (PCE) of 33.89%. Two main wastes were identified: overprocessing at the packing station and transportation delays due to trolley shortages, causing each unit to be delayed by 39.35 seconds. Improvements included modifying the packing table and shelves based on operator anthropometrics and adding trolleys to key workstations. After these changes, the lead time dropped to 103.75 seconds per unit, and PCE increased to 45.54% (an 11.65% gain). As a result, production output rose by 26%, from 265 to 313 units per day, enabling the company to better meet customer demand.

S. Jing et al. [95] demonstrated that implementing the P-VSM (Procurement Value Stream Mapping) in manufacturing significantly reduced inventory, shortened purchasing cycles, lowered product prices, and increased market competitiveness. Their experimental analysis with company TY showed that applying P-VSM, along with lean concepts, streamlined information and material flows, improving procurement efficiency by over 90%. P-VSM helped eliminate excess inventory, delays, and procurement inefficiencies, while reducing non-value-added time and resource waste. It also enabled flexible, customer-focused procurement, reduced scrap and raw material waste, increased production flexibility, and improved both business efficiency and product quality. The study confirmed that P-VSM is a scientific and effective tool that can be widely adopted for warehouse procurement management.

A. Deshkar et al. [96] presented a Lean Manufacturing framework for small businesses based on Value Stream Mapping (VSM). By mapping the current state, they identified wastes such as inactivity, underproduction, excess WIP, long TAKT times, and scheduling issues. Simulations helped reveal the causes of these wastes. Using VSM tools, they eliminated non-value-added activities and developed a future state map, increasing the value-added portion of lead time from 15% to 89.85%. TAKT time was reduced from 46.6 to 26 minutes, daily rolling output increased to 50, and the pacemaker cycle time was shortened, accelerating operations. Work order scheduling was optimized to meet high demand and reduce machine and worker overload. The simulation results were shared with XYZ management for review and implementation.

D. Steven et al. [97] identified three main types of waste—rework, unnecessary motion, and excess transport—in the construction of shop houses in Eastgate, Surabaya. By addressing these, they found that 6.88 hours out of 172.87 total hours (about 4%) could be saved. Solutions included enforcing strict quality control to reduce rework, increasing supervision to cut down on unnecessary motion, and improving material distribution by sending plastering and finishing materials directly to work sites to minimize excess transport. Some non-value-added activities, like casting dimension fireplaces, could be eliminated, though many additional tasks remain necessary for construction despite adding little value.

M. Sadeque et al. [98] used Lean methodology to improve the workstations at "XYG Company," aiming to reduce processing and lead times. They recommended purchasing raw materials as needed, maintaining Lean practices, using electronic welding helmets to boost welding duty cycles from 16% to 35%, and replacing MIG welding with spot/projection nut welding. Value Stream Mapping (VSM) was used to identify and eliminate inefficiencies. Additional suggestions included allowing staff to operate at multiple stations, eliminating waiting for loaf cutting, relocating raw materials closer to the mixing station, promoting energy-saving practices, implementing Just-In-Time production, and using recycled materials for packaging. The primary wastes addressed were unnecessary transportation, improper processing, overproduction, and waiting. Implementing these solutions could reduce lead time by 20.28 minutes per cycle and lower energy use by 0.13 kWh per cycle.

R. Lufika et al. [99] identified two potential improvements using CSM and FSM: allowing workers to operate at multiple stations and eliminating waiting during loaf cutting. Additionally, four options using EVSM and FEVSM were proposed, such as relocating raw materials closer to the mixing station, posting reminders to turn off motors, adopting Just-In-Time production, and using recycled packaging. The main wastes in peeled loaf production were unnecessary transportation, improper processing, overproduction, and waiting. Implementing FSM solutions could reduce lead time by 20.28 minutes per cycle and lower energy consumption from 11.45 kWh to 11.32 kWh per cycle.

L. Xu et al. [100] demonstrated that Value Stream Mapping (VSM) is an effective Lean management tool for visualizing and identifying process problems (PPs), while DMAIC offers a structured approach for solving them. However, VSM alone does not provide solutions, and DMAIC does not identify PPs. By combining both in the VSM-DMAIC framework, VSM identifies and groups PPs, and DMAIC addresses them, enabling concurrent Lean-Kaizen improvements. In a case study on air-conditioner installation, the framework improved the assembly line's LOB rate, average WIP, and supply delays, delivering significant economic benefits—797,051 RMB profit per month. This was the first practical application of VSM-DMAIC in production. Additionally, VSM was applied in small-scale paving block manufacturing, where inefficiencies such as material transport and weather-related losses were addressed. Improvements included layout changes, covering sand storage, and setting daily output targets, which reduced material transfer costs and production time. Overall, Lean Manufacturing—especially VSM—helped streamline processes, increase productivity, and cut costs. The study suggests integrating further Lean tools like 5S or Kaizen for sustained long-term improvements and greater operational efficiency.

C. Maylani et al. [101] found that applying Lean Manufacturing concepts, especially Value Stream Mapping (VSM), significantly reduced waste in the paving industry. At Paving Agung Lestari, inefficiencies such as poor material transportation, sand loss due to weather, and the absence of daily output targets were identified. Solutions like layout changes and reducing unnecessary movements cut transportation time and saved IDR 12,502,500 in material transfer costs. Covering the sand storage area reduced material loss and setting daily production goals improved consistency and managed demand. These measures reduced the production time for 750 paving blocks from 16 hours and 15 minutes to 15 hours and 52 minutes. Overall, Lean Manufacturing and VSM streamlined production, boosted productivity, lowered costs, and improved resource management. The study suggests that further improvements could be achieved by integrating 5S or Kaizen methods for sustained efficiency gains.

S. Lie et al. [102] analyzed the use of Value Stream Mapping (VSM) in improving batch chemical production at an Indonesian herbicide manufacturer. By applying Lean principles and VSM to assess the current process, they identified improvements that reduced manufacturing lead time by 30% and demonstrated a strong ROI from these changes. To further enhance efficiency, the company was advised to renegotiate supplier agreements for better alignment with customer demand, collaborate with engineering contractors for reactor maintenance, and formalize Lean initiatives to maintain employee engagement. While the case focused on a single site, which may limit broader applicability, the study suggests that future research could explore the effects of changeovers on productivity and lead time, as well as use simulation to optimize inventory and batch sizes in response to demand variability.

M. Santoso et al. [103] used Lean Manufacturing and Value Stream Mapping (VSM) to optimize floating wheel production. Their analysis identified waste from waiting times, inefficient material movement, and excessive inspections. Current state mapping showed that only 40.4% of production time added value. Implementing a Future State VSM reduced total lead time by 25% (from 17,790 to 13,330 seconds), increased value-added time to 44.8%, and eliminated three unnecessary process stages, thereby simplifying the workflow.

S. Rahima Shebeen et al. [104] used Lucid-chart to create a present state value stream map for wall panel fabrication at a precast manufacturing unit, revealing a maximum lead time of 1,102 minutes and daily output of 33 components. After implementing improvement strategies, a future state map showed reduced lead time (739 minutes) and increased output (40 components per day).

The study introduced a leanness metric, CPM (Continuous Performance Measurement), to assess gains in efficiency and effectiveness, which improved by 49% and 21.2%, respectively. Overall, Value Stream Mapping reduced lead time, increased production, and enhanced value and productivity in the precast plant.

M. Salwin et al. [105] used Value Stream Mapping (VSM) to analyze and optimize the production processes of a steel pipe manufacturer for upholstered furniture. Improvements led to a 17% increase in slitting line productivity and a 1.7-fold reduction in polypropylene tape waste. Enhancements to slitting line spare parts also improved operator comfort and safety. The Availability index—a measure of scheduled time versus task completion time—rose from 67% to 79%, reflecting a shift from non-value-added to necessary non-value-added activities, even though it didn't directly shorten production cycles. The study noted a limitation of VSM: its static nature, as production conditions can change daily. The authors recommended combining VSM with simulation models for more accurate, dynamic analysis. Future efforts should focus on new technologies, environmental protection, and resource efficiency to further improve production.

J. Matindana et al. [92] showed that Lean manufacturing, through Value Stream Mapping (VSM), can identify and eliminate non-value-added activities by analyzing material and information flow. While VSM has significantly reduced lead time and work in progress in other industries, its application in Tanzania's agricultural sector was underexplored. Their study applied VSM to rice milling, using time and motion analysis to find and merge non-value-added tasks, reducing preliminary lead time from 15 to 6 minutes. Overall, cycle time and lead time were reduced by 0.04 min/kg and 9.3 minutes, respectively. These improvements increased throughput, profitability, and competitiveness, potentially creating more jobs and aiding staff retention. The study suggests that integrating VSM with Industry 4.0 tools for real-time monitoring could further enhance efficiency and decision-making in the future.

D. Lubis et al. [106] found that in the oil palm sorting division at PT. Karya Tanah Subur, activities such as transporting fruit to the sorting area, waiting, and loading/unloading were identified as non-value-added processes. The current state showed 72% of activities were non-value-added, with a process cycle efficiency of 27.34%. After reducing and eliminating these activities, the future state map reflected a drop to 53% non-value-added activities, an increase to 47% value-added activities, and improved process cycle efficiency to 46.91%. The study concluded that improvements should address people, materials, methods, and the environment for the best results.

S. Yuniar et al. [107] found that implementing recommended strategies could significantly reduce manufacturing waste at PT. By applying these suggestions, non-value-added tasks could be reduced from 62.08% to 37.28%. The improvement plan includes establishing a standard operating procedure for product inspection that also addresses material handling.

S. M. Mustaquim et al. [108] found that value stream mapping enabled Lean teams to visualize and improve target processes, leading to reduced inventory, costs, and inefficiencies. In a furniture upholstery case, cost-based value stream mapping was used to propose process improvements. Implementing these changes was expected to yield a 50% increase in process cycle efficiency, a

24.8% rise in value-added time, a 60% reduction in non-value-added time, and a 6.17% decrease in production lead time. Additionally, projected weekly spending would drop by 11.25%. The analysis assumed staff adherence to Lean principles and did not account for human factors. Data collection was challenged by industry regulations, requiring some estimates. The study suggests further research into ergonomics and environmental aspects for even better results.

M. Singgih et al. [109] used a cost-integrated value stream (CI-VS) approach to identify waste-related expenses and losses in production. The study found that reducing pipe rejects and excess inventory would help streamline production and lower costs. By applying activity-based costing, the company can implement more effective improvements, enhancing production efficiency and profitability.

K. Chang et al. [110] applied lean manufacturing and Value Stream Mapping to analyze and improve the assembly line for product P during a transformation project. Lean practices enhanced line layout, process flow, production mode, material buffering, auxiliary equipment, and manpower allocation, effectively reducing waste and non-value-added activities. The new assembly line enabled mass production of product P, boosting efficiency, cutting labor intensity, saving costs, and increasing staff awareness of lean principles. The study demonstrated the successful transition from traditional to lean production.

Z. Ikatrinasari et al. [111] found that in the current state value stream map (SVSM) for the stamping process, the total lead time was 1,742.5 minutes, with only 13% (235.5 minutes) spent on value-added activities and 1,507 minutes on non-value-added tasks. The stamping department consumed 43,695.3 kWh of energy—17,476.9 kWh for stamping itself and 26,218.4 kWh for transportation and material handling. The future SVSM proposed improvements that could reduce lead time by up to 15%, bringing it down to 1,477.5 minutes. Recommendations included implementing SMED (Single-Minute Exchange of Die) to perform setup tasks while the machine is running and replacing TL lamps with LED lights to lower energy use.

M. Habib et al. [112] conducted an experiment in a packaging and accessories industry where reducing lead time was a challenge. Value Stream Mapping (VSM) was used to identify bottlenecks and their impact on processes. The study found that waiting for material flow caused significant delays, especially in die cutting. Implementing Lean Manufacturing System (LMS) and VSM reduced inventory and setup time in die cutting by 9.6% and boosted equipment efficiency by 15%. In the finishing area, adding color-coded stickers to products improved sorting, accountability, and product information, reducing the Internal Complaint Rate (ICR) by 55% and improving the organizational KPI (CCR) by 83%. A new floor layout in the finishing stage minimized motion, allowing for a 13.04% increase in processed items and a 13.3% rise in Units Per Labor Hour (UPLH). Overall, VSM-driven lean manufacturing made the process more efficient, flexible, and competitive while significantly reducing lead time.

2.9. Kanban

Kanban, derived from the Japanese words for "signboard," is a visual scheduling and inventory control system created by Toyota to manage production effectively. It ensures a smooth flow of value while preventing system overburdening. In footwear manufacturing, for example, processes like leather cutting, stitching, and packaging must be synchronized for efficiency. Kanban's visual representation of material and task flow enables teams to pinpoint bottlenecks or shortages, facilitating prompt adjustments.[113]

M. Cano et al. [113] found that Kanban's visual management enabled quick understanding of production status, while the Kaizen approach fostered continuous, just-in-time improvement and informed decision-making. This combination promoted a collaborative, empowered culture and ongoing process improvement. As a result, the studied footwear company achieved lower inventory levels, shorter wait and cycle times, greater adaptability to changes, and overall increased efficiency.

R. Ratnayake et al. [114] demonstrated that combining a pull system with Kanban is highly effective in manufacturing, as seen in a labor-intensive textile plant. Despite frequent line stoppages over two weeks, production output increased by 22%, and the proper number of Kanban cards at collection points indicated efficient implementation. The plant also used lean practices like setup reduction, TPM, and TQM, which supported the success of the Kanban system. The study noted that Kanban cards would not flow efficiently if machine breakdowns or quality issues were high, highlighting the importance of these supporting tools. Additionally, a highly skilled workforce, as shown by the operator skill matrix, was essential for Kanban system success.

S. Aldouri [115] found that integrating JIT-Kanban with digital twin technology significantly improved operational performance for small and medium-sized manufacturing enterprises (SMMEs) in Saudi Arabia's Eastern Province. In a 30-month study involving twelve automotive parts manufacturers, digital twin models achieved high accuracy (correlation coefficients of 0.89–0.96) and real-time manufacturing control with data syncing every 2.33 seconds. The framework resulted in substantial reductions: inventory by 47.3%, lead times by 28.4%, equipment inefficiency by 38.6%, and expenses by 7.3%, thus boosting profits and yielding an estimated 187% ROI with a median implementation cost of $127,000 and an 18-month payback.
Digital maturity, not company size, was the strongest predictor of successful adoption ($r = 0.87$, $p < 0.001$). Firms with higher digital readiness adopted Industry 4.0 technologies more quickly and recouped investments faster. The framework's effectiveness (78.3% success rate) far outperformed traditional JIT approaches (31.2%). However, the study's findings are limited by its specific regional and time context and the absence of a randomized control group. The research suggests further studies in diverse regions and over longer periods to better assess scalability and long-term impact.

A. Diekola et al. [116] used action research to improve warehouse storage space utilization, leading to significant benefits. Storage capacity was reduced from 1,800 to 1,050 pallets, saving RM 232,000 annually. Eliminating inventory repackaging and double handling cut warehouse staff from 24 to 15, saving another RM 324,000 per year. Enhancing part quality allowed production supervisors to focus on value-added tasks, reducing unnecessary administrative work. Communication improved with a unified platform (Dropbox), and implementing a Supplier Kanban System further streamlined operations and improved conditions, resulting in total annual savings of about RM 556,000.

V. Pasha et al. [117] found that production time losses were caused by issues related to the environment, people, procedures, and machines. Delays included waiting for machine programs, product checks, and wrapping, as well as cleaning and improving products. The study improved four-wheeled vehicle spare part production by rearranging assembly and inspection areas, implementing e-Kanban and manual Kanban, and enhancing cleaning procedures. These changes reduced process time for one batch by 41.22% (from 17.10 to 10.05 days) and increased monthly production by 128.65% (from 42,917 to 60,157 units). The study suggests that integrating Lean Manufacturing with Green Manufacturing could further boost cost efficiency and sustainability by reducing processing times and production defects that harm the environment.

M. Alghazali et al. [118] found that excess inventory across raw materials, work in progress, and finished goods led to high storage costs and inefficiencies in the absence of a Kanban system. Implementing Kanban was projected to reduce inventory levels by 25–75%, lowering associated costs such as security, electricity, and depreciation, and improving product quality by supporting long-term survival. Visual workplace organization and workflow improvements made materials easier to locate and sped up process transitions, enhancing responsiveness to customer demand and reducing inventory obsolescence.
Value Stream Mapping (VSM) and Kaizen burst events further reduced non-value-added activities, cutting processing time from 78 to 61 days, non-value-added time from 42 to 30 hours, and order-making time from 11 to 9 weeks. Waste was reduced from 3% to 2%, and manufacturing inventory dropped from 858 to 806 tons. These continuous improvements improved factory performance, reduced changeover times, and streamlined various production phases, demonstrating the effectiveness of Kanban and Kaizen in optimizing operations.

K. Gupta et al. [119] found that Lean manufacturing tools—such as time studies, value stream mapping, and Kanban—revealed no direct correlation between production lead time and processing time. Ineffective direction and communication resulted in significant idle time and non-value-added activities. Introducing a centralized Kanban communication system and a redesigned VSM improved interdepartmental communication, reduced idle time, and enabled better tracking of time spent on tasks. Managers could more easily adjust process times and responsibilities. After implementing the Kanban system, lead time was reduced by 2,520 minutes and process efficiency increased from 34% to 85%.

N. Salazar-Medina et al. [120] found that, with proper application, standardization, and worker commitment, Lean Manufacturing tools significantly reduced waste and unproductive time, increasing fabric cutting productivity to 87.56%—a 9.44% improvement. The 5S tool enhanced workspace organization, Kanban and Poka-Yoke improved flow and defect control, and SMED minimized waiting times, reducing cycle time and boosting efficiency. Overall, Lean

Manufacturing tools proved effective in improving efficiency, effectiveness, and productivity, making them valuable for streamlining and optimizing manufacturing processes.

L. Eduardo Canales Jeri et al. [121] demonstrated that implementing Kanban and Just-In-Time (JIT) significantly improved the competitiveness of a Peruvian textile SME. Simulation results showed the company reduced its faulty item rate from 12%—1.2% above the industry average—and late deliveries dropped from 60% to 29.9%. Production control, identified as a major factor in productivity decline, was improved through the use of Kanban cards and boards, which enhanced real-time monitoring and reduced errors. As a result, garment production rates nearly doubled, increasing from 8.34 to 15.86 garments per hour.

S. Kumar et al. [122] found that implementing a kanban-CONWIP pull system in a bearing manufacturing environment significantly improved inventory control, production responsiveness, and process efficiency. Using real-time operational data, lean practices reduced work-in-progress (WIP) by 27.79% and substantially decreased replenishment times in traditional manufacturing settings. Their study's unique contribution was the practical, shop-floor application of the kanban-CONWIP system, relying on actual measurements rather than simulations or models.

3. LEAN MANUFACTURING

Lean manufacturing, introduced by Jim Womack and colleagues in their 1991 book "The Machine that Changed the World," emphasizes systematically eliminating waste from production processes, drawing inspiration from the Toyota Production System. Although the term "lean" is relatively new, many of its tools and methods trace back to early 20th-century practices by Fredrick Taylor and the Gilbreths. Lean manufacturing integrates proven industrial engineering techniques to boost efficiency in diverse settings. The following sections will detail the specific procedures and applications of lean manufacturing.

J. Zaga-Quispe et al. [123] demonstrated that a continuous improvement model increased productivity in a plastic SME's extrusion process by 4.97% (from 0.21 to 0.22), boosting overall efficiency. Using conventional work tools reduced waste by 30.44%, the largest improvement noted. Implementing SMED reduced setup time by 9.77% through outsourcing some internal tasks, cutting wasted time. TPM, focusing on quality maintenance, lowered defective rolls by 28.38%, which decreased the company's return rate.

D. Setyadi et al. [124] concluded that:

1. Analysis of the seven waste categories in flowline pipeline construction identified the main causes of project delays. The most significant waste was waiting, primarily due to material delays, poor coordination, access and weather issues, and equipment failures. Suggested mitigation strategies include selecting reliable suppliers, enforcing delay penalties, improving coordination, providing workforce training, and offering incentives. Defect waste was caused by supplier material faults and construction errors, such as pipe dents

and welding defects, requiring skilled welders, strict supervision, and compliance with welding procedures. Transportation waste occurred from inefficient pipe handling, slow loading, and long distances between sites, exacerbated by poor road conditions.

2. Initially, value-added activities accounted for 62.8% and non-value-added for 37.2%. After applying Process Activity Mapping (PAM) improvements, value-added activities increased to 69.1%, and non-value-added dropped to 30.9%.
3. The Supply Chain Risk Management (SCRM) study found a cumulative inventory of 667 days and a cumulative lead time of 250 days, totaling 917 days.
4. Enhancing company-supplier information systems, improving interdepartmental communication, and reducing cycle times for wasteful tasks can further boost process efficiency.

J. Journal et al. [125] found that at PT XYZ, waste levels in tapioca flour production varied by category, with transportation, overprocessing, and unnecessary motion being the most significant. Initially, the production process had a lead time of 1,429 minutes, a process cycle efficiency (PCE) of 63.89%, and 913 value-added activities. After implementing improvements—such as using stronger wooden boards for waste transfer, clearing flour deposits, using burlap sacks for safer movement, ensuring more precise initial separation, and introducing trolleys—lead time dropped to 1,194 minutes, and PCE increased to 76.47%, a 12.58% improvement. These changes, guided by fishbone diagram analysis and updated SOPs, enhanced efficiency and reduced waste in the production process.

A. Das et al. [126] increased productivity in a medium-sized manufacturing sector by applying various lean and industrial techniques without adding costs, resources, or labor. Using time studies and Value Stream Mapping (VSM), they separated value-added (VA) and non-value-added (NVA) activities and eliminated bottleneck NVA activities from the current VSM to meet delivery expectations. The study focused on VSM, layout optimization, and line balancing, achieving notable improvements without extra staff or major process changes. These methods could be further expanded across the organization, complemented by other lean tools like 5S, TPM, and SMED for greater production optimization.

M. Manurung et al. [127] recommended classifying Lean Manufacturing (LM) by technique, scope, principles, and supports. Their analysis found that Value Stream Mapping was used in 70.7% of case studies. LM principles emphasize pull production/just-in-time, workflow simplification, and the cultivation and education of human resources. The authors suggest further research, especially since LM is now applied beyond manufacturing, indicating its potential for use and study in a variety of other industries.

S. Borgave et al. [128] demonstrated that applying lean manufacturing to a GPP compressor line effectively eliminated non-value-added tasks. Key findings include:

1. Lean tools such as Value Stream Analysis, FMEA, Takt time, and kaizen improved cycle time, workspace flexibility, and reduced worker movement, boosting productivity.
2. FMEA identified waste sources and helped prioritize process improvements.

3. Cycle time decreased by 25.8% (Block section) and 24.1% (Package section), non-value-added activities dropped by 35.6% and 28.1%, flexible space increased by 38% and 140%, and worker distance was cut by about half.
4. The improvements enabled the production line to meet a monthly demand of 12 machines with shorter cycle times and provided extra buffer for future growth.

I. Jayanti et al. [129] identified multiple wastes in outpatient pharmacy services at Drs. H. Amri Tambunan Hospital, including waiting, unnecessary movement, defects, overproduction, labor waste, and inefficient transportation across various pharmacy activities. Key causes of waiting times were a lack of pharmacists, doctors not following formulary guidelines, insufficient staff training, poor hospital information systems, non-standard pharmacy layout, and limited drug availability. To address these, the study recommended reorganizing the pharmacy, staff training, creating SOPs and flowcharts, forming a pharmacy control team, implementing an integrated information system, hiring more dispensing pharmacists, and improving drug procurement. Additionally, delays in BPJS claim payments should be managed with better financial control to ensure timely medicine supply.

J. Zvidzayi [130] found that Lean manufacturing practices benefit the economy, society, and environment by reducing inventory, improving product quality, minimizing waste, enhancing flexibility, and lowering costs, thus supporting operational sustainability. Lean transformations led to improved work routines, environments, teamwork, and employee empowerment, which strengthened social sustainability, as seen in higher morale and collaboration. Environmental gains included energy savings, waste and pollution reduction, and cleaner production systems. In the automotive sector, converting waste into raw materials and finished products further demonstrated Lean's combined economic, social, and environmental sustainability benefits.

4. LEAN SIX SIGMA

F. Nurprihatin et al. [131] used the DMAIC approach to identify five types of waste in mooncake production: transportation, waiting, over-processing, defects, and inventory. The analysis showed that waiting was the most significant waste, contrary to the initial hypothesis that defects would be the worst. Lean Six Sigma (LSS) tools, including a recommendation plan and 5S, were applied to reduce waste, resulting in a projected increase in process cycle efficiency (PCE) from 66.19% to 70.98%, and a reduction in production cycle time from 0.498 to 0.486 seconds per piece. Product loss decreased from 25,146 to 12,508 pieces and lost time from 194 to 87 minutes. The study advises the company to track inventory, implement LSS recommendations, maintain preventive maintenance programs, and establish a quality control department. Reliability Centered Maintenance (RCM) and research on SOP compliance and human factors are also recommended to further reduce downtime and improve productivity.

T. Lean et al. [132] demonstrated that Lean Six Sigma (LSS) significantly improved quality, productivity, and efficiency in the textile spinning industry. By combining Lean methods to reduce waste and Six Sigma tools to minimize variation, the study analyzed a dataset of 193,695 cones over three months, finding an initial defect rate of 10.69%. Root cause analysis identified major issues like yarn breakage, poor maintenance, and inconsistent quality processes. Implementing stricter maintenance, standardized procedures, and better training reduced defects by 56.3% to 4.67%, raising the process sigma level and saving about PKR 25.3 million per month. The results show that LSS is a practical, sustainable strategy for enhancing technical quality and profitability in textile spinning, helping mills remain competitive globally.

V. Yadav [133] reviewed literature on Lean, Green, and Six Sigma practices, identifying theoretical gaps and distinguishing between theory and simulation components. The study highlighted seven key research gaps and noted that existing research often narrowly addresses the integration of lean and green practices. The review proposed a combined Lean, Green, and Six Sigma framework, integrating Lean and Green approaches with the Six Sigma DMAIC methodology. The analysis also identified 15 barriers that can hinder the implementation and integration of these approaches in manufacturing. The ISM method was recommended for identifying these barriers, while MICMAC analysis helped classify them as dependent, linkage, or driving barriers. The study concluded that understanding and addressing these obstacles can help employers and professionals achieve sustainable business management.

M. Anjar et al. [134] analyzed quality control at Jhono Garment, finding that T-shirt products had a potential defect rate of 6,097 per 1,000,000 items and a sigma value of 4.006, with waste defects being the most common issue. Defect repairs cost IDR 5,000–10,000 each and took 10–30 minutes to fix. Introducing folding molds for the folding process eliminated packing faults in a production trial, completely reducing packing errors. However, the study did not conduct a comprehensive waste analysis, which limited further waste reduction efforts.

5. GREAN MANUFACTURING

Green manufacturing is an integrated engineering system that includes subsystems such as green design, manufacturing, quality assurance, recycling, resource management, environmental assessment, and supporting databases. Its main goal is to develop models guiding the adoption of green manufacturing technologies. Core aspects involve using eco-friendly materials and renewable energy sources (like solar and wind), conserving energy, and managing product life cycles to minimize environmental impact. Green manufacturing centers on three key elements: green design processes, efficient resource use, and product lifecycle management for recycling and reuse. It employs three approaches—raising environmental awareness, applying technical solutions to environmental issues, and improving management and staff quality. Overall, its two main objectives are resource efficiency and environmental protection, achieved by optimizing design and manufacturing processes for sustainability and energy conservation.[135]

K. Rakesh et al. [136] found that environmental considerations play a significant role in shaping industrial strategy, making green manufacturing essential for managers and executives. The study developed a structured model linking sustainability, waste reduction, and greener practices with productivity, and used quantitative indicators to assess current processes and suggest improvements. The proposed plan prioritizes raw material use, energy efficiency, and operational enhancements while balancing market demands and cost reduction.

Key findings include:

- Economic benefits and business reputation are the strongest drivers of green manufacturing.
- Environmental issues and legislation are also important, emphasizing regulatory compliance and sustainability.
- The random regression model explained 88% of the variation in green manufacturing success, showing strong predictive power.
- Stakeholder involvement and innovation further promote sustainability.
- Economic conditions and industry competition have less impact, suggesting some drivers are less aligned with sustainability.
- The importance of drivers like employee requests and logistics varies by industry and organization.

The study concludes that focusing on high-impact drivers, while addressing weaker ones, will help firms advance green manufacturing, achieve sustainability goals, and foster growth.

A. Purnomo et al. [137] analyzed global academic literature on green manufacturing and observed a growing trend in research output. China was the leading contributor with 520 publications, followed by Chongqing University and researcher Liu, F. Engineering was the main discipline, with 999 publications (36.7%), and "Applied Mechanics and Materials" was the most frequent source. The field peaked in 2019 with 177 publications. Six collaborative research patterns were identified. The study introduced a classification axis to map out three decades of knowledge across areas such as machining, environment, sustainable development, energy, manufacturing, computer science, and tools. This mapping helps highlight major research themes, trends, and gaps, guiding future studies to address deficiencies and deepen understanding. The analysis, based on the Scopus database and limited to titles, abstracts, and keywords, provides a simplified overview of the field. The authors recommend future research to integrate data from multiple databases (Scopus, Web of Science, EBSCO, SciELO) for a more comprehensive analysis of green manufacturing's impact and development.

S. Liang [138] showed that green manufacturing is vital for green construction machinery, as it improves resource efficiency, reduces production costs, and lessens environmental harm. Green manufacturing supports the development of a circular economy and is integral to sustainable progress and China's development policies. Advancing green manufacturing requires integrating "green" principles throughout the product life cycle, using sustainable design practices, eco-friendly materials, green technologies in production, and environmentally responsible waste treatment to minimize pollution.

Green manufacturing involves using raw materials efficiently, optimizing processes, strictly controlling product quality, and integrating these efforts with environmental protection to balance economic and ecological goals. B. Chen et al. [139] researched machining technologies for green manufacturing and found that careful selection of machining tools and optimized use of cutting fluids can improve the efficiency and sustainability of the process. They proposed a model to assess the environmental impact of different manufacturing process elements and introduced a comprehensive evaluation formula to score green manufacturing process designs for their sustainability and functionality.

Ya. Li et al. [140] developed a Productivity Abatement Index (PAI) using data from European paper, pulp, and coke industries (1995–2006) to assess how carbon abatement affects environmental productivity. The study found that focusing on transforming resources boosts productivity, while emphasizing only converted resources can reduce it. Countries with strong innovation capabilities achieve better environmental productivity through carbon reduction. The Kyoto Protocol had a positive effect, but the EU Emissions Trading System (EU ETS) negatively impacted production in terms of carbon abatement. The study recommends evaluating technologies for efficient carbon reduction, developing advanced machinery, and considering the entire product life cycle in emissions assessments. Policymakers should promote R&D in carbon reduction, encourage academic–industry partnerships, and carefully design regulations to balance pollution control with resource optimization. The study notes limitations due to its time frame and calls for more research in different sectors and on various pollutants to improve understanding of environmental impacts.

M. Javaid et al. [141] demonstrated that green manufacturing promotes environmental sustainability by integrating green technologies and considering the entire product life cycle—from research and production to use and disposal. This includes designing energy-efficient digital devices (like computers and printers), minimizing waste during production, reducing energy consumption, and promoting responsible use. Green computing offers promising environmental benefits. Advanced remanufacturing, supported by automation and AI, is transforming traditional recycling, making the acquisition, processing, and disassembly of complex products more efficient and cost-effective. This shift enhances the viability of reverse logistics and supports the circular economy, particularly in industries such as consumer lighting products.

6. LEAN AND GREAN MANUFACTURING

Lean (LM) and green (GM) manufacturing both aim to reduce non-value-added activities and boost operational performance, and their combined application—known as the Lean and Green (L&G) paradigm—has gained attention in industry and academia. While both approaches focus on waste reduction and efficiency, they have distinct emphases: LM centers on cost and operational efficiency, while GM prioritizes lowering environmental impact. There are misconceptions that L&G is synonymous with lean alone, but research shows LM and GM are complementary, jointly enhancing operational and environmental outcomes. Lean tools like 5S and SMED can also support green goals. Integrating lean practices with green initiatives results in better waste management and operational efficiency, demonstrating their interdependence in manufacturing. [142]

R. Kaur et al. [142] conducted a survey across various Saudi manufacturing SMEs to explore the integration of lean, green, and lean-green practices. Their quantitative analysis found that awareness of the benefits of lean and green approaches is growing among Saudi practitioners, especially regarding operational and environmental sustainability. The results showed that combining lean and green (lean-green) strategies leads to greater improvements in both operational and environmental performance compared to using green practices alone. This research adds to the literature by providing benchmarks for standardizing lean-green practices in Saudi Arabia, promoting more sustainable manufacturing. However, the study's limitations include the potential oversimplification of complex realities by surveys, biases from using Likert scales, and the reliance on participant honesty and engagement for the validity and reliability of results. Supplementing quantitative data with open-ended questions helped provide deeper insights.

W. Leong et al. [19] examined the foundations of lean and green (L&G) practices, finding that their synergy enhances both operational and environmental performance. The study reviewed L&G principles, tools, implementation challenges, and industry barriers. Results showed that a lack of commitment from government and industry policymakers hindered L&G adoption, while strong top-down organizational support led to more successful implementation. A key barrier was the shortage of qualified staff. The L&G model identified people, machines, materials, money, and environmental factors as crucial components. By simulating L&G implementation, the proposed model aims to address current research gaps and accelerate adoption. The article also provides guidance for industrialists to better understand L&G and develop strategies for improving facility sustainability.

Z. Ikatrinasari et al. [111] found that the current stamping process had a lead time of 1,742.5 minutes, with only 13% of that time spent on value-added activities (235.5 minutes) and the rest (1,507 minutes) on non-value-added tasks. The stamping department consumed 43,695.3 kWh of energy—17,476.9 kWh for stamping and 26,218.4 kWh for transportation and material handling. By implementing SMED (Single-Minute Exchange of Die) for both external and internal processes, lead time could be reduced to 1,477.5 minutes—a 15% improvement. Additional recommendations included replacing TL lamps with LEDs, and optimizing air conditioning and condenser airflow to further save energy.

P. Dungani Rudi et al. [143] found that introducing Lean and Green (L&G) fundamentals helps beginners grasp both concepts and their synergy, leading to improved environmental and operational performance. The study identified barriers such as lack of knowledge, poor planning, and absence of supportive government policies, which hinder effective adoption in industry, particularly SMEs. Successful L&G implementation requires full management commitment, but a shortage of expertise prevented integrated management after obstacles were identified. The proposed L&G model incorporates Men, Material, Machine, Money, and Environment as core elements. Their simulation model aims to bridge research gaps and accelerate L&G adoption.

K. Jbira et al. [144] observed that lean management is often implemented alongside green initiatives, focusing on environmental goals. However, they noted situations where green practices may conflict with lean business objectives. This raises important questions for future research, such as identifying which lean practices might negatively impact the environment and exploring how green methods could replace or improve upon them.

T. Elsoud et al. [145] found that environmental assessments in various industries revealed issues with low productivity and quality. To improve these sectors, there is growing concern among investors and manufacturers about recycling, reuse, and regulatory compliance. The study emphasized eliminating the concept of waste and fostering a healthier environment through thoughtful design and management. It highlighted the strong connection between waste-free and green philosophies, both of which prioritize waste reduction. Lean and green initiatives in the marble industry included measures such as creating tree barriers to reduce pollution and increase greenery, optimizing raw material storage to minimize transportation, promoting renewable energy use (like natural gas), and modernizing production processes and equipment to enhance efficiency and environmental friendliness.

W. Dong et al. [146] addressed global manufacturing challenges like global warming and resource depletion by developing a new lean and green (L&G) model optimized with backpropagation (BP). Their framework guides industrialists in shifting from current practices to L&G operations using the 4M1E approach (Money, Material, Manpower, Machine, and Environment). They created novel 4M1E indicators tailored for the processing industry, noting that traditional static models fail to reflect real-world fluctuations. The paper's innovation lies in applying BP algorithms to make analytical models adaptive, enabling them to update and improve over time and in response to changing conditions. This dynamic approach helps industries continuously enhance their lean and green practices.

M. Dora et al. [147] found that the adoption of lean and green practices in SMEs remains low. In a packaging manufacturing SME case study, Value Stream Mapping (VSM) and Root Cause Analysis (RCA) were used to identify both lean and green wastes. The study introduced the Green Integrated Value Stream Mapping (GIVSM) tool, which enables the simultaneous implementation of lean and green initiatives to enhance both operational and environmental performance.
In the pilot study, GIVSM—supported by Kaizen, visual management, SOPs, quality control, and supplier selection—reduced lead time by 63% and carbon footprint by 77%. However, one challenge was the increased energy demand to mold extra units, which created a misalignment between operational efficiency and environmental goals. The study recommended reinvesting cost and carbon savings into sustainable production, including eco-friendly materials, efficient transportation, renewable energy, and local suppliers, as part of a continuous improvement cycle. Overall, the GIVSM methodology helped identify areas where lean and green practices align or conflict and provided a structured approach for SMEs to synergistically improve efficiency and sustainability, even when facing funding or resource constraints.

R. Rathi et al. [148] described Green Lean Six Sigma (GLSS) as a comprehensive approach that delivers high-quality, eco-friendly products while minimizing environmental impact. The goal of GLSS is to improve key performance indicators (KPIs) such as quality, profitability, customer satisfaction, process efficiency, and responsiveness. The study emphasized the integration of GLSS, focusing on intangible factors like toolkits and enablers, with teamwork and management commitment identified as the most important facilitators for successful implementation in manufacturing. The proposed GLSS framework helps manufacturing organizations adopt best practices to minimize defects and environmental impact, making it easier to produce high-quality, sustainable products.

B. Lyna [60] demonstrated that Green Lean Six Sigma (GLSS) can transform sustainable manufacturing by integrating Lean Six Sigma (LSS) methods with environmental strategies to maximize efficiency and minimize environmental impact. This integration enhances efficiency, reduces emissions, and supports the circular economy. Successful GLSS implementation requires systematic integration, strong leadership, workforce engagement, and technology adoption. Its impact should be measured using environmental (emissions, energy use, waste), economic (cost, resource efficiency), and social (staff well-being, community engagement) sustainability KPIs.
To fully realize GLSS's benefits, organizations must address cultural and technological barriers. Case studies in both established and developing countries have highlighted GLSS's positive effects, but further research is needed to assess sustainability outcomes, broaden applications, and refine performance measurement methods. Incorporating Industry 4.0 technologies such as IoT and Cyber-Physical Systems (CPS) can further optimize GLSS by enabling real-time data-driven decisions and process automation. The synergy of GLSS with Industry 5.0 technologies promises even greater sustainability and efficiency through smart, real-time systems, despite ongoing challenges.

M. Kaswan et al. [149] presented a GLSS (Green Lean Six Sigma) framework that integrates Green, Lean, and Six Sigma approaches to minimize production waste and enhance manufacturing productivity, employee well-being, and environmental performance. The GLSS model uses 3R principles (reduce, reuse, recycle), aims for minimal rejection, and seeks continual improvement. While implementing GLSS in developing countries like India faces challenges such as lack of experience, limited technology, and resistance to change, it can still boost customer satisfaction, value, industrial efficiency, and organizational goals.
The study introduced a systematic framework that combines DMAIC (Define, Measure, Analyze, Improve, Control) with GLSS, providing managers with the tools to enhance sustainability regardless of organization size or type. However, the study is conceptual and has not been practically implemented, so its real-world application awaits further research. Kaswan et al. suggest that future work could integrate Green Lean Six Sigma with Industry 4.0 and circular economy approaches, and propose developing manufacturing sector models that address both barriers and solutions for effective GLSS implementation.

S. Lintang et al. [150] found that eliminating energy use and emissions as forms of environmental waste was a key priority. By applying Process Activity Mapping (PAM) to the production process at Sentra Batik Ayu Arimbi, energy consumption and cycle time were both reduced. Switching from firewood to gas and optimizing electricity use saved IDR 2,192,018 per batch. The Future State Environmental Value Stream Mapping led to a 3.9% reduction in cycle time and a 14% decrease in energy use. Additionally, emissions from the batik stamp production process dropped by 63% after implementing these energy-saving measures and replacing firewood with gas.

R. Ridwan Alief et al. [151] identified several types of waste—such as defects, delays, and excessive processes—on the CV wifi sectoral antenna production line at Global Access Technology. By applying Green Value Stream Mapping, they reduced the total manufacturing lead time from 15,749 seconds to 13,796 seconds. This resulted in an increase in value-added time from 76.78% to 87.62%, marking a 10.84% improvement in value-added activities.

6.1. Integrated Lean–Green (L&G) Framework

The advent of Industry 4.0 has introduced significant techno-economic challenges, requiring industry participants to adopt advanced technologies to remain competitive. Industry 4.0, characterized by digitalization and IoT-enabled smart factories, has profoundly changed industrial development, manufacturing, and business models by integrating intelligent production processes. As a result, new Lean & Green (L&G) standards have been developed for manufacturing.
Manufacturing performance can be enhanced through systematic data collection and analysis, which supports improvements in output, quality assurance, and process efficiency. To adapt to Industry 4.0, companies need smart sensors, adaptive decision-making tools, advanced models, intelligent devices, and robust data analytics. However, the high investment required for these technologies creates a gap between implementation and industry confidence, especially given global competition.
The proposed L&G process flow aims to bridge this gap by enabling manufacturers to achieve continuous process improvement and better performance through data-driven methods—before committing to the higher costs of full Industry 4.0 adoption. Factory instrumentation and real-time data evaluation are essential for ongoing improvement, allowing companies to build trust in the transition and enjoy incremental gains at a lower initial investment.

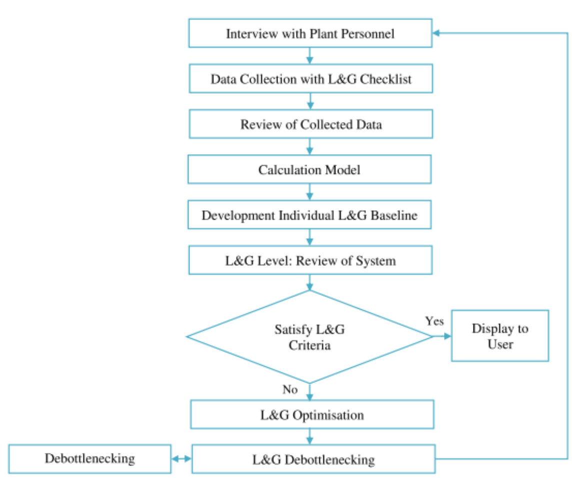

Fig.1. Proposed Lean and Green process flow chart [152]

Figure 2 showed a proposed L&G framework for “data collection with L&G checklist”. The proposed Lean & Green (L&G) framework expands on the traditional 5M (man, material, machine, methods, money) by adding the “environment” component, ensuring both operational efficiency and environmental sustainability. The five key components of the L&G framework are:

1. **Personnel (Manpower):** Emphasizes creating a supportive environment for employees, essential for adapting to new technologies and maintaining competitiveness through talent development.
2. **Money:** Focuses on cost savings, efficiency, sustainability, and serves as a key performance indicator for organizational success.
3. **Machine:** Highlights the importance of optimizing machinery performance to improve production efficiency and motivate ongoing staff development.
4. **Material:** Covers raw materials, finished goods, logistics, storage, and quality, ensuring efficient and sustainable material management.
5. **Environment:** Incorporates environmental considerations to prevent negative impacts like global warming and climate change, representing the framework’s “green” focus.

This framework provides a check-and-balance approach to guide organizations during L&G implementation, supporting clear decision-making and accelerating adoption. It also aims to integrate a multiple-criteria decision-making (MCDM) tool to help organizations make informed choices based on operational behavior.

The framework addresses gaps in Industry 4.0, which often neglects environmental aspects, by encompassing both operational and environmental concerns. The use of simulation—a key Industry 4.0 technology—is predicted to grow, aiding integrated analysis and process automation. Case studies and literature suggest that Industry 4.0 can reduce production, logistics, and quality management costs by 10%, but often overlooks green issues.

Overall, the L&G framework is designed to overcome barriers to L&G adoption, fill the implementation gap, and guide industry players toward more sustainable and efficient manufacturing under Industry 4.0. Future research will focus on applying this framework in real industrial settings to validate its impact on facility operating performance.

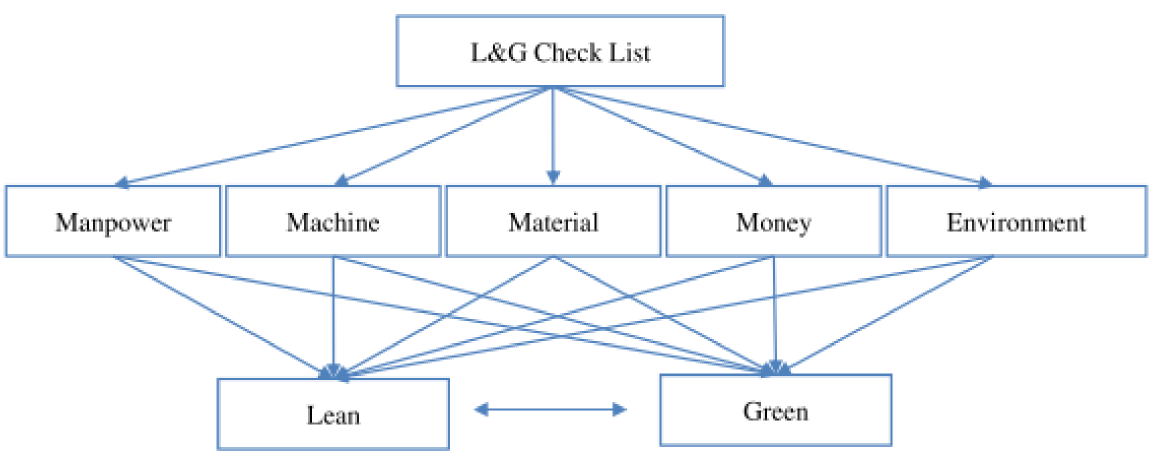

Fig.2. Proposed Lean and Green manufacturing framework. [152]

The integration of Green and Lean practices offers enterprises a promising avenue to improve sustainability performance. Research has shown that organizations that implement both lean and green strategies together achieve better results than those focusing on just one. However, a major limitation has been the lack of a comprehensive framework for applying Green and Lean methodologies, especially in SMEs.

To address this gap, a targeted integrative framework is proposed, based on theoretical elements identified through literature review and modeled after an IDEF0 diagram structure. This conceptual framework outlines the essential components needed for SMEs to achieve sustained profitability through cost reduction, while also upholding environmental and social responsibility. At the framework's core is Green-Lean integration, with key success factors acting as inputs, and performance outcomes (including trade-offs between economic, social, and environmental goals) as outputs. Identified obstacles represent the rules and constraints influencing organizational efforts to improve sustainability. Finally, the framework includes mechanisms—such as specific tools and methodologies—to facilitate and enhance Green-Lean integration. While conceptual, this framework aims to guide SMEs in effectively implementing and benefiting from combined lean and green practices.

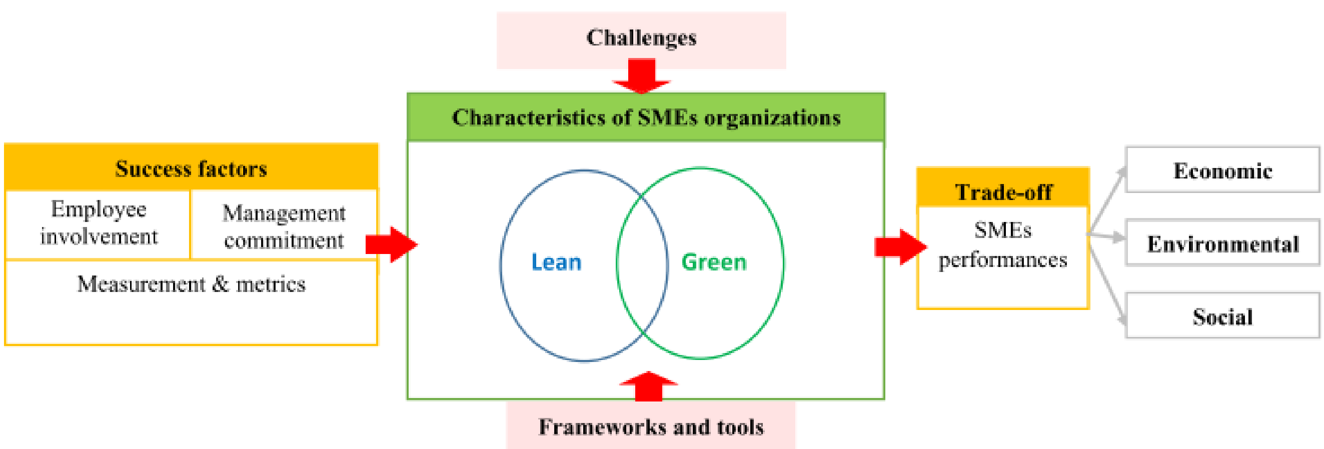

Fig. 3. Framework for Green-Lean approach for SMEs. [153]

7. Discussion

The literature review clearly shows that Lean Manufacturing (LM) tools—such as SMED, VSM, 5S, Kaizen, and RCA—not only improve operational efficiency but also support environmental goals, especially when properly implemented. LM's focus on eliminating waste (Muda) directly aligns with environmental waste reduction, creating a strong foundation for integrating Lean and Green practices.

SMED, in particular, is highlighted for its ability to reduce changeover times by 17% to over 80%, increasing machine availability and reducing energy and waste. However, additional resources needed for SMED could introduce environmental costs, so balanced decision-making is necessary.

VSM and 5S also play key roles by identifying inefficiencies and improving workplace organization, safety, and material management—making them practical, cost-effective options for SMEs. However, while Lean and Green initiatives often complement each other, there can be conflicts: for example, Just-in-Time (JIT) can reduce inventory but increase transportation emissions, and smaller batch sizes can raise energy use due to frequent changeovers. This shows that Lean is not automatically Green, and environmental metrics must be included to ensure comprehensive sustainability.

Industry 4.0 technologies—like IoT sensors, analytics, and digital twins—help bridge these gaps by providing real-time data for optimizing both operational and environmental performance. Such digital tools strengthen the integration of Lean and Green by validating process improvements and supporting continuous enhancement.

The success of Lean–Green integration depends on leadership, staff involvement, and shared performance metrics, but SMEs often face resource and expertise limitations. A recommended approach is to start with basic Lean practices, add environmental assessments, and gradually incorporate digital tools.

In summary, Lean–Green integration offers significant potential for competitive advantage and sustainability, but achieving full benefits requires explicit environmental assessments, addressing trade-offs, and leveraging digital technologies. Future research should focus on quantifying environmental gains from Lean tools and developing digital support for ongoing Lean–Green alignment.

CONCLUSION

This research shows that combining Lean Manufacturing (LM) and Green Manufacturing (GM) is an effective strategy to boost both operational performance and environmental sustainability. Key Lean tools—such as 5S, SMED, VSM, Kaizen, RCA, and JIT—consistently reduce waste, stabilize processes, and improve efficiency, which in turn leads to lower energy use, reduced CO_2 emissions, less material waste, and better resource use. When Lean is implemented with explicit environmental goals, it naturally supports Green outcomes.

However, successful Lean–Green integration requires more than just using the right tools. Leadership commitment, a supportive corporate culture, employee involvement, and digital technologies from Industry 4.0 (like IoT, analytics, and real-time monitoring) are crucial for sustaining improvements in efficiency and sustainability. The review also notes potential conflicts, such as increased transportation from JIT or the environmental impact of SMED tooling, stressing the need to include environmental metrics—like energy use, emissions, and waste—in Lean initiatives to avoid unintended negative impacts.

Integrating LM and GM into a unified Lean & Green (L&G) framework offers a strategic advantage for factories seeking greater competitiveness and sustainability, especially for SMEs looking for cost-effective solutions. Future research should focus on quantifying the environmental benefits of specific Lean tools, validating the L&G framework in different industries, and exploring how digital transformation and Industry 4.0 can further enhance Lean–Green synergies. With these improvements, Lean–Green integration can become a core element of modern sustainable manufacturing.

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