BIS ENERGY AND ENGINEERING

Volume 3 2026 | DOI: 10.31603/biseeng.588
7th Borobudur International Symposium on Science and Technology (BIS-STE) 2025

UNIMMA PRESS
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Integration of lean-green manufacturing and simulation modeling for sustainable production efficiency improvement

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Abstract

Manufacturing industries are increasingly required to improve production efficiency while reducing environmental impacts. However, many production systems still experience long lead times, high energy consumption, and excessive material waste. This study aims to develop an integrated Lean–Green Manufacturing framework supported by simulation modeling to improve both operational performance and environmental sustainability. The research was conducted by first identifying production inefficiencies using Value Stream Mapping and lean assessment tools. Environmental indicators, including energy consumption and material waste, were then incorporated into the improvement analysis. A discrete-event simulation model was developed using Arena software to represent the current production system and to evaluate alternative Lean–Green improvement scenarios before real implementation. The simulation results show that the integrated Lean–Green scenario provides significant improvements compared to the existing system. Total production lead time was reduced by 23.2%, cycle time decreased by 20.2%, and production throughput increased by 21.2%. In addition, energy consumption was reduced by 21.0%, while material waste decreased by 27.9%, indicating a substantial improvement in environmental performance. These findings demonstrate that integrating Lean and Green approaches, validated through simulation modeling, can effectively enhance production efficiency while supporting sustainable manufacturing objectives. The proposed framework also serves as a practical decision-support tool for industries seeking to implement sustainability-driven improvements with minimal operational risk.

Published:
May 04, 2026

Selection and Peer-review under the responsibility of the 7th BIS-STE 2025 Committee

Keywords

Lean-green manufacturing, Sustainable production, Simulation modeling, Industrial engineering, Energy efficiency

Introduction

Manufacturing industries are currently facing increasing pressure to achieve higher productivity while simultaneously reducing environmental impacts. The demand for shorter lead times, efficient resource utilization, and lower energy consumption has become a critical concern in modern production systems [1]. These challenges are not limited to large-scale industries but are also experienced by medium and small manufacturing enterprises that operate with constrained resources and high process variability [2]. As a result, improving production efficiency while maintaining environmental responsibility has become a central issue in the field of industrial engineering. These challenges highlight the need for systematic approaches that address both operational efficiency and environmental sustainability in manufacturing systems.

Table 1. Key challenges in sustainable manufacturing systems [2, 3]

Challenge Category	Description	Impact on Manufacturing Performance
Operational Efficiency	Long lead times and process imbalance	Reduced responsiveness and productivity
Resource Utilization	Excessive material waste and rework	Increased production cost and inefficiency
Energy Consumption	High energy usage during production and idle states	Increased environmental footprint
Environmental Pressure	Emission and waste regulations	Compliance risks and sustainability concerns

As shown in Table 1, efficiency-related and environmental challenges are closely interconnected, indicating the need for integrated improvement strategies rather than isolated solutions. Various approaches have been proposed to address these challenges. Lean Manufacturing has been widely applied to eliminate non-value-added activities and improve operational efficiency through tools such as Value Stream Mapping, waste identification, and process standardization [4]. In parallel, Green Manufacturing has gained attention as a strategy to reduce environmental impacts by focusing on energy efficiency, material optimization, and waste minimization. Previous studies have reported that both approaches can independently improve production performance and sustainability indicators when implemented properly.

More recently, researchers have suggested that Lean and Green approaches are complementary and can generate greater benefits when applied together. Several studies have explored Lean–Green integration to reduce waste and environmental burdens simultaneously [6]. In addition, simulation modeling, particularly discrete-event simulation, has been increasingly used to analyze complex production systems and evaluate improvement strategies without disrupting real operations. Simulation enables decision makers to test multiple scenarios, identify bottlenecks, and assess system behavior under different conditions. Previous studies have addressed these challenges through different approaches, which can be broadly classified into Lean-focused, Green-focused, and simulation-based methods.

Table 2. Overview of existing manufacturing improvement approaches [7, 8]

Approach	Primary Focus	Strengths	Limitations
Lean Manufacturing	Waste elimination and efficiency	Shorter lead time, higher productivity	Limited focus on environmental impact
Green Manufacturing	Energy and environmental performance	Reduced emissions and resource use	Often lacks operational efficiency analysis
Simulation Modeling	System behavior evaluation	Risk-free scenario testing	Often excludes environmental indicators
Lean-Green Integration	Combined efficiency and sustainability	Potential synergistic benefits	Frequently lacks quantitative validation

Table 2 illustrates that although various approaches have been proposed, each method still exhibits limitations when applied independently. Despite these developments, existing studies often treat Lean, Green, and simulation as separate or partially connected tools. In many cases, Lean–Green integration is discussed conceptually without quantitative validation, or simulation is applied solely to evaluate operational performance without explicitly incorporating environmental indicators [9, 10]. As a result, there is still limited understanding of how an integrated Lean–Green framework can be systematically developed and validated using simulation to support sustainable production decision-making, particularly in injection molding and similar manufacturing environments. A closer examination of previous studies reveals several aspects that remain insufficiently explored.

Table 3. Research gap and proposed contribution

Aspect	Existing Studies	Gap Identified	Proposed Contribution
Lean-Green Integration	Mostly conceptual discussions	Limited quantitative evaluation	Simulation-based validation
Environmental Indicators	Often discussed separately	Not embedded in lean analysis	Integrated performance metrics
Decision Support	Qualitative recommendations	Lack of risk-free testing	Scenario evaluation using simulation
Industrial Context	Generic manufacturing systems	Limited application in injection molding	Context-specific framework

Despite the growing interest in Lean–Green integration, limited studies provide a quantitatively validated framework that simultaneously evaluates operational efficiency and environmental performance using simulation modeling, particularly in injection molding environments in Table 3. Therefore, this study aims to develop and validate an integrated Lean–Green Manufacturing framework using discrete-event simulation (Arena) to quantitatively assess its impact on lead time, throughput, energy consumption, and material waste [11, 12]. The proposed framework is intended to serve as a decision-support tool that enables risk-free evaluation of sustainability-driven production improvements. This study addresses the following research question: How can an integrated Lean–Green framework validated through discrete-event simulation improve both operational and environmental performance in manufacturing systems? While previous studies often emphasize either conceptual integration or partial simulation analysis, limited research provides a complete and quantitatively validated Lean–Green integration workflow tailored to energy-intensive injection molding operations.

Method

Research design and framework

This study adopts a quantitative, model-based research design using an integrated Lean–Green Manufacturing framework supported by discrete-event simulation. The research focuses on evaluating production efficiency and environmental performance improvement scenarios through systematic waste identification, environmental indicator assessment, and simulation-based analysis [13]. The overall research framework follows a sequential approach to ensure reproducibility and logical consistency between the method and result sections.

Study object and data sources

The object of this study is a selected production process within an injection molding manufacturing system. The process was chosen due to its high energy consumption, repetitive production cycles, and sensitivity to operational inefficiencies. Data were obtained from:

1. Direct observation of the production line,
2. Time studies of each workstation,
3. Production records and operational logs,
4. Energy consumption data obtained from machine power ratings and operational duration, and
5. Material waste data recorded from scrap and rework reports.

All data were collected during normal operating conditions to reflect actual system behavior.

Waste identification using value stream mapping

Value Stream Mapping (VSM) was employed to analyze the current state of the production system. The mapping process included identifying process sequences, processing times, waiting times, and work-in-process inventory levels. Lean waste categories, including waiting, motion, defects, over processing, and unnecessary energy usage, were systematically identified [13]. The current-state VSM served as the baseline model for further Lean–Green integration and simulation development.

Green indicator assessment

To incorporate environmental performance into the analysis, several Green indicators were evaluated:

1. Energy consumption per process, calculated based on machine operating time and rated power,
2. Material waste generation, measured from scrap and rework quantities, and

3. Environmental load proxy, estimated using standardized emission factors associated with energy usage.

These indicators were embedded into the improvement analysis to ensure that environmental impacts were considered alongside operational efficiency.

Lean–green integration strategy

Lean and Green principles were integrated by linking identified Lean wastes with corresponding environmental indicators. For example, excessive waiting and idle time were associated with unnecessary energy consumption, while defects and rework contributed directly to material waste [4, 7]. Based on this integration, improvement strategies were formulated, including:

1. Line balancing to reduce waiting time,
2. Standardization of operating procedures to minimize variability,
3. Idle energy reduction through improved machine scheduling, and
4. Material handling optimization to reduce scrap.

Simulation model development

Process time data collected from time studies were statistically analyzed to determine appropriate probability distributions. Input Analyzer in Arena was used to fit the data, and triangular or normal distributions were applied depending on goodness-of-fit results and sample size adequacy. The simulation was run under steady-state conditions with an 8-hour production horizon per replication. A warm-up period of 30 minutes was applied to eliminate initial bias effects. Each scenario was simulated using 30 independent replications to ensure statistical reliability of the results. Queuing logic between workstations followed a First-In-First-Out (FIFO) discipline, with work-in-process buffers modeled as finite-capacity queues reflecting actual shop-floor conditions. Machine breakdowns were not explicitly modeled, assuming stable operating conditions during the observation period. Environmental load was estimated using standardized emission factors based on electricity consumption, expressed as kg CO_2-equivalent per kWh, following national energy conversion references. Energy-related emissions were treated as proxy indicators rather than direct real-time measurements.

Improvement scenario design

Three improvement scenarios were designed and evaluated using the simulation model:

1. Lean-focused scenario, emphasizing waste elimination and process balancing,
2. Green-focused scenario, targeting energy reduction and material efficiency, and
3. Integrated Lean–Green scenario, combining both efficiency and sustainability strategies.

Each scenario was simulated under identical production demand conditions to ensure fair comparison.

Performance measurement and analysis

System performance was evaluated using the following indicators:

1. Total production lead time,
2. Cycle time,
3. Production throughput,
4. Machine utilization,
5. Energy consumption,
6. Material waste generation, and
7. Work-in-process inventory.

Simulation results from the current state and improvement scenarios were compared to quantify the impact of the proposed Lean–Green integration framework. Statistical comparison between scenarios was conducted using mean output values and 95% confidence intervals obtained from multiple simulation replications.

Methodological novelty

The methodological novelty of this study lies not merely in combining Lean, Green, and simulation approaches, but in structuring them into a sequential and fully integrated workflow specifically applied to injection molding production systems [13, 15]. Unlike prior studies that evaluate operational or environmental aspects separately, this framework embeds energy consumption and material waste indicators directly into the Value Stream Mapping analysis and validates improvement scenarios quantitatively using discrete-event simulation. This structured integration provides a comprehensive, measurable, and context-specific decision-support model tailored for energy-intensive injection molding environments.

Results

This section presents the main findings of the study following the chronological order of the research methodology.

Current state performance

The current state analysis shows that the production system experiences several inefficiencies that affect both operational and environmental performance [16]. Based on the Value Stream Mapping analysis, excessive waiting time and work-in-process inventory were observed across multiple workstations. These inefficiencies contribute to a relatively long total production lead time of 18.05 minutes per unit and a cycle time of 52.04 seconds. From an environmental perspective, the current production system exhibits high energy consumption, particularly during machine idle states. Daily energy usage reached 1,240 kWh, while material waste generation amounted to 86 kg per day, mainly due to scrap and rework activities. The average machine utilization rate was 78%, indicating unbalanced workloads and underutilized resources. The current-state Value Stream Mapping provides a comprehensive overview of material and information flow across the production system.

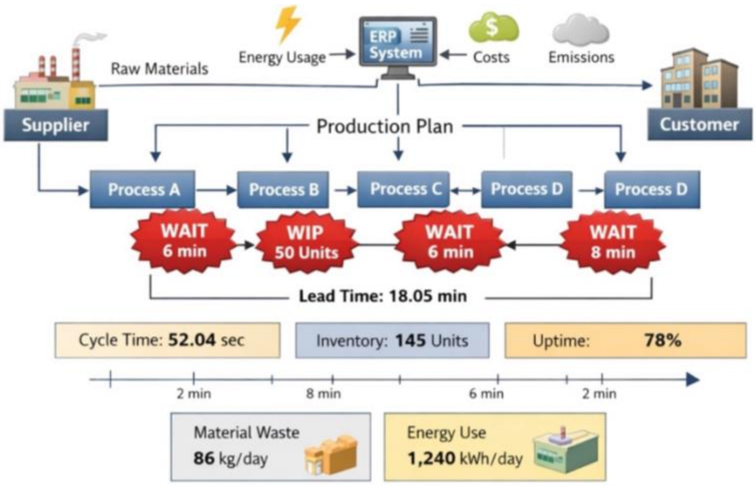

Figure 1. Current-state value stream mapping of the production system

As illustrated in Figure 1, excessive waiting time and work-in-process inventory are observed between several workstations, contributing significantly to prolonged lead time. Quantitative performance indicators of the current production system are summarized in Table 4.

Table 4. Current State Performance Metrics

Performance Indicator	Current State Value
Total lead time (min/unit)	18.05
Cycle time (sec)	52.04
Throughput (units/day)	920
Energy consumption (kWh/day)	1.240
Material waste (kg/day)	86
Machine utilization (%)	78
Work-in-process (units)	145

These baseline values serve as the reference point for evaluating the effectiveness of the proposed improvement scenarios.

1. Lean–green improvement scenarios

Three improvement scenarios were evaluated using discrete-event simulation: Lean-focused, Green-focused, and integrated Lean–Green scenarios. Among these, the integrated Lean–Green scenario demonstrated the most significant overall performance improvement [17, 18]. Simulation results indicate that the integrated scenario reduced total production lead time from 18.05 to 14.02 minutes per unit, representing a 23.2% reduction. Cycle time was reduced by 20.2%, primarily due to reduced waiting time and improved process balance. Production throughput increased from 920 to 1,115 units per day, reflecting a 21.2% improvement. Environmental performance also improved substantially. Energy consumption decreased from 1,240 kWh/day to 980 kWh/day, achieving a 21.0% reduction. Material waste generation decreased from 86 kg/day to 62 kg/day, corresponding to a 27.9% reduction. Additionally, machine utilization increased from 78% to 86%, while work-in-process inventory decreased by 25.5%, indicating a more stable and efficient production flow.

Table 5 presents a comparative summary of the simulation results for the current state and all improvement scenarios.

Table 5. Simulation Results of Improvement Scenarios

Indicator	Current State	Lean Scenario	Green Scenario	Lean-Green Scenario
Lead time (min/unit)	18.05	15.40	16.10	14.02
Cycle time (sec)	52.04	44.80	47.10	41.55
Throughput (units/day)	920	1.050	1.000	1.115
Energy use (kWh/day)	1.240	1.110	1.030	980
Material waste (kg/day)	86	71	68	62
Machine utilization (%)	78	83	81	86
WIP (units)	145	118	123	108

The integrated Lean–Green scenario consistently achieves the best performance across all operational and environmental indicators. Figure 2 illustrates the comparative impact of each improvement scenario on lead time and energy consumption.

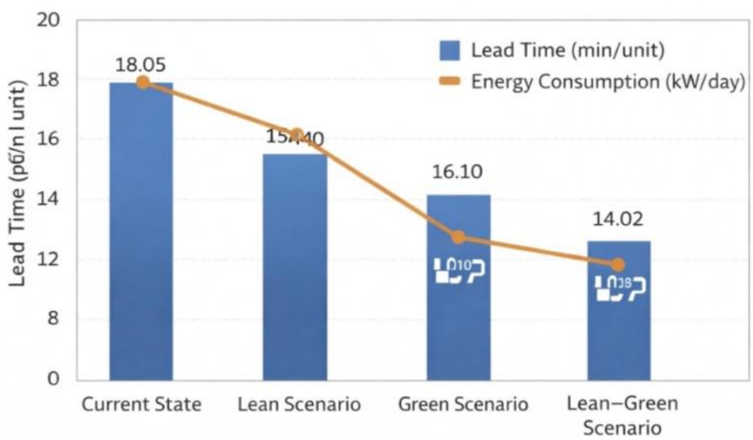

Figure 2. Comparison of Lead Time and Energy Consumption

The Figure 2 highlights the synergistic effect of Lean–Green integration, where efficiency improvements also translate into significant energy savings.

Summary of key findings

Overall, the simulation results demonstrate that integrating Lean and Green strategies leads to simultaneous improvements in production efficiency and environmental performance. The integrated Lean–Green scenario consistently outperformed single-focus scenarios across all evaluated indicators, confirming its effectiveness as a comprehensive improvement approach [19]. To clearly demonstrate the magnitude of improvement, percentage changes achieved by the integrated Lean–Green scenario are summarized in Table 6.

Table 6. Percentage Improvement of Lean-Green Scenario

Indicator	Improvement (%)
Lead time reduction	23.2
Cycle time reduction	20.2
Throughput increase	21.2
Energy savings	21.0
Waste reduction	27.9
WIP reduction	25.5

Sensitivity to demand variation and managerial implications

To assess the robustness of the improvement strategy, additional simulation runs were conducted under varying demand levels (±10% of baseline demand). The integrated Lean–Green scenario maintained superior performance compared to the current state, although system utilization increased under higher demand conditions. Under increased demand, the balanced configuration demonstrated better adaptability, with lower queue growth compared to the current state system. However, if demand exceeds 15% above baseline capacity, additional workforce or parallel inspection stations may be required to prevent new bottlenecks. From a managerial perspective, these findings suggest that Lean–Green integration is not only effective under normal operating conditions but also relatively robust against moderate demand fluctuations. Decision-makers should therefore consider workload balancing and idle energy monitoring as priority actions in injection molding environments.

Discussion

This section discusses the implications and meaning of the research findings in relation to the research objectives and existing knowledge in the field.

Interpretation of operational performance improvements

The reduction in total lead time and cycle time indicates that the elimination of waiting and process imbalance plays a critical role in improving production efficiency. These results directly address the first research objective, which aimed to enhance operational performance through integrated Lean–Green strategies. The increase in throughput and machine utilization further suggests that the production system becomes more responsive and capable of meeting demand under the improved scenario. These findings support the fundamental Lean principle that waste elimination contributes to improved flow and productivity [20]. By embedding these principles within a simulation-based framework, the study demonstrates how operational improvements can be evaluated quantitatively before real-world implementation. The reductions in lead time and cycle time observed in Table 5 indicate improved flow stability and reduced waiting across the system.

Interpretation of environmental performance improvements

Idle energy reduction was primarily achieved by minimizing waiting time between molding cycles and downstream processes. In the current state, machines remained powered during downstream bottlenecks, consuming standby electricity. By balancing workstation capacities and reducing queue buildup, machine idle duration decreased substantially. Additionally, improved scheduling reduced unnecessary start–stop frequency, which is particularly energy-intensive in injection molding operations due to barrel heating requirements. Material waste reduction was strongly linked to improved inspection consistency and early defect detection. By stabilizing upstream processes, the frequency of rework and scrap generation declined, directly contributing to the 27.9% waste reduction.

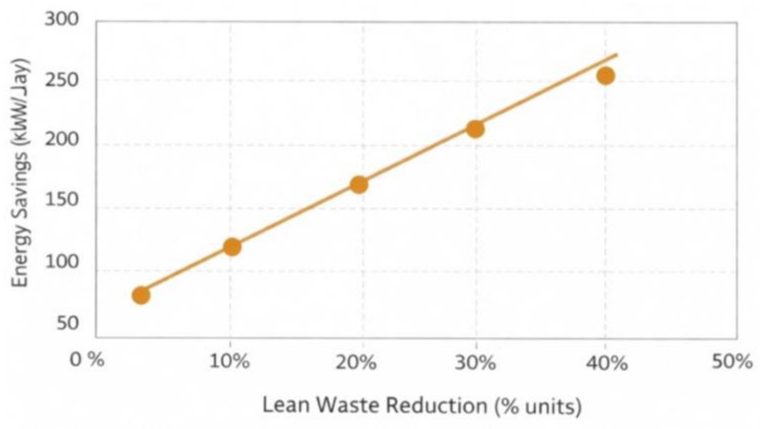

Figure 3. Relationship Between Lean Waste Reduction and Energy Savings

Implications of simulation-based validation

One of the most significant contributions of this study lies in the use of discrete-event simulation as a validation tool. The simulation model allows improvement scenarios to be tested virtually, reducing the risk associated with direct implementation. This approach provides strong support for management decisions by quantifying the expected benefits of Lean–Green integration under realistic operating conditions [22]. The findings demonstrate that simulation modeling not only complements Lean–Green analysis but also strengthens its credibility by providing measurable and reproducible results. Table 7 positions the findings of this study within the broader context of Lean–Green research.

Table 7. Comparison with Typical Findings in Lean–Green Studies

Aspect	This Study	Typical Previous Studies
Validation method	Simulation-based	Conceptual / case observation
Environmental indicators	Embedded in model	Evaluated separately
Risk-free testing	Yes	Limited
Decision support capability	High	Moderate

Novelty and Research Contribution

The novelty of this research lies in the systematic integration of Lean waste identification, Green performance indicators, and simulation modeling within a single evaluation framework. Unlike approaches that apply Lean or Green methods independently, this study demonstrates how their integration can produce synergistic benefits that are quantitatively validated through simulation [23, 24]. While the results are specific to the studied production system, the proposed framework offers a structured and replicable approach that can be adapted to other manufacturing environments with similar characteristics.

Limitations and Future Research Implications

Although the results demonstrate clear improvements, this study is limited by its reliance on simulation rather than real-world implementation. Additionally, environmental performance was evaluated using proxy indicators rather than real-time sensor data [25]. Future research should explore the integration of real-time energy monitoring systems, advanced optimization algorithms, and supply chain-level analysis to further enhance the robustness and applicability of the proposed framework.

Conclusion

This study confirms that integrating Lean–Green principles with discrete-event simulation enables simultaneous operational and environmental performance improvements. By quantitatively validating improvement scenarios before implementation, the proposed framework strengthens decision-making reliability in sustainable manufacturing contexts. The discussion highlights those operational improvements, such as reducing waiting time and balancing production flow, inherently contribute to environmental performance enhancement when energy consumption and material waste are explicitly considered. This confirms that efficiency-driven initiatives and sustainability objectives are not conflicting goals but can be achieved in parallel through structured integration. A significant contribution of this study lies in the methodological perspective. By embedding environmental indicators into Lean analysis and validating improvement scenarios using simulation, the proposed framework advances current industrial engineering practices beyond conceptual discussions. The use of simulation as a decision-support tool enables manufacturers to assess the potential impact of sustainability-oriented strategies without disrupting actual operations, thereby supporting more informed and reliable decision-making. From a broader perspective, this work contributes to the evolving body of knowledge in sustainable manufacturing by demonstrating a practical pathway to align operational excellence with environmental responsibility. The framework provides a replicable structure that can be adapted to various manufacturing contexts, supporting the transition toward more sustainable production systems. Future research should focus on extending the framework through real-time environmental data acquisition, integration with digital manufacturing technologies, and application across different industrial settings. Such developments would further strengthen the validity and scalability of the proposed approach and support continuous advancement in sustainable industrial system design.

Acknowledgement

The authors would like to express their sincere gratitude to all parties who supported the completion of this research. Special appreciation is extended to the management and technical staff of the manufacturing facility for granting access to production data and operational information necessary for this study. The authors also acknowledge the contributions of colleagues and students who assisted in data collection, observation, and model verification during the research process. Their support and cooperation were essential to the successful execution of the study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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