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Lean Green and Smart Manufacturing: Ecosystem Strategies for Sustainable Innovation

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Abstract - Can a traditionally resource- and emission-intensive industry become a global benchmark for sustainability and efficiency? This study demonstrates that it can. Focused on the metalworking sector, we propose a powerful integration of Lean Green and Smart Manufacturing (LGSM) strategies—combining waste reduction, energy optimization, and circular resource use with cutting-edge technologies like cyber-physical systems and predictive maintenance. Through the application of the Fuzzy Analytic Hierarchy Process (FAHP) and consultation with seven industry experts, we prioritized the key drivers of sustainable transformation. The findings are clear: Waste Reduction in Production (WRP) leads the way, achieving a maximum importance of 50.15% and averaging 31.21% across evaluations. Lean-based Energy Optimization (LDEO) ranks second, peaking at 38.40% and averaging 27.92%. In the technological dimension, Cyber-Physical Systems for Sustainability (CPS-S) dominate with a weight of 39.32%, while Smart Predictive Maintenance (SPM) secures 17.99%. Sustainable innovation factors such as Energy Efficiency (EE) and Internet of Things (IoT) also show notable influence, averaging 17.52% and 10.60%, respectively. Overall, this research outlines a strategic roadmap, proving that aligning environmental goals with technological capabilities is essential for building the sustainable, digital, and resilient industries of the future. These insights offer valuable guidelines for practitioners and policymakers aiming to accelerate the transition toward sustainable manufacturing.

Keywords: Lean Green, Smart Manufacturing, Sustainable Innovation, Metalworking, Efficiency.

1. Introduction

The metalworking industry faces significant environmental challenges due to its high energy consumption, pollutant emissions, and industrial waste generation. The imperative to adopt sustainable practices has become increasingly evident, driven by regulatory pressures and market expectations that demand a reduction in environmental impact without compromising production efficiency [1]. A critical issue in this sector is the management of metal waste and the excessive consumption of natural resources, necessitating the implementation of circular economy principles and energy optimization strategies [2]. Moreover, sustainability in metalworking extends beyond waste reduction, encompassing water conservation, carbon emissions mitigation, and the design of products with lower environmental impact throughout their lifecycle [3].

Addressing these challenges requires a commitment to technological innovation, the development of recyclable materials, and the enforcement of stringent environmental regulations to ensure more responsible production processes aligned with sustainability objectives [4].

The integration of Lean Green principles within manufacturing operations is essential for enhancing both operational efficiency and environmental sustainability. Lean methodologies prioritize waste reduction and process optimization, while Green Manufacturing emphasizes the incorporation of eco-friendly strategies to minimize environmental impact [5]. The adoption of digital technologies, including artificial intelligence and Industry 4.0 advancements, further reinforces Lean Green initiatives by enabling real-time, data-driven decision-making and predictive analytics for process optimization. Additionally, the implementation of eco-intelligent production systems is pivotal in striking a balance between industrial efficiency and environmental responsibility, thereby facilitating the transition toward low-carbon manufacturing [6]. Achieving sustainability in manufacturing also necessitates investments in environmentally friendly production technologies and the alignment of corporate strategies with regulatory frameworks and evolving consumer expectations. Furthermore, the evolution from Industry 4.0 to Industry 5.0 fosters a more human-centric and sustainable manufacturing ecosystem, ensuring long-term competitiveness while addressing global sustainability challenges.

The manufacturing industry has evolved through successive technological revolutions, leading to the emergence of Industry 4.0, where digitalization and interconnectivity optimize efficiency, costs, and sustainability. However, the adoption of these technologies faces barriers such as implementation complexity and uncertainty regarding return on investment. In sectors like manufacturing, the integration of digital architecture represents a key opportunity to enhance asset utilization and energy efficiency [7]. The implementation of I4.0 transforms manufacturing by integrating digital technologies such as IoT, artificial intelligence, and additive manufacturing, optimizing operational efficiency and sustainability. Despite advancements, the adoption of I4.0 in emerging economies faces challenges due to technological gaps and limited workforce training [8].

The application of these three methodologies is fundamental to addressing this research. Smart Manufacturing (SM) integrates Cyber-Physical Production Systems (CPPS) and the Internet of Things (IoT) to optimize real-time production planning and execution, driving digital transformation and continuous improvement in Industry 4.0. Its implementation in SMEs enhances operational efficiency, reduces costs, and optimizes data-driven decision-making [9]. In parallel, industrial sustainability demands a reduction in carbon emissions, where green hydrogen emerges as a viable alternative, though it faces economic and regulatory barriers. Through Structural Equation Modeling (SEM), it is demonstrated that its integration with digitalization strengthens manufacturing sustainability and guides more sustainable industrial strategies [10]. In this context, adopting Lean Green principles in manufacturing is crucial to improving both operational efficiency and environmental sustainability by combining waste reduction with ecological strategies.

The structure of this document is as follows: Section 2 provides the literature review; Section 3 examines the application of the Lean Green methodology; Section 4 explores the implementation of Smart Manufacturing; and Section 5 outlines the integration of the Sustainable Innovation methodology.

2. Literature review

A. Lean Green: Key Strategies and Benefits

The integration of Lean Green principles in manufacturing has become a cornerstone for companies striving to achieve environmental sustainability without compromising operational performance. At the core of this approach is Waste Reduction in Production, which aims not only to minimize resource waste but also to streamline processes for enhanced productivity and profitability. As noted in [11], implementing Lean methodologies, such as value stream mapping, Kaizen, and just-in-time (JIT) systems, significantly reduces waste while simultaneously improving process efficiency and quality outputs. Moreover, [12] highlights that digitalization, including IoT-based real-time monitoring and AI-driven predictive analytics, serves as a transformative enabler. These technologies enable early detection of issues and support quick decisions to reduce waste and improve production agility.

B. The Strategic Role of Circular Economy

A fundamental pillar supporting Lean Green initiatives is the Integration of Circular Economy practices, which advocate for sustainable resource use by extending the lifecycle of products and materials. [13] argue that strategies such as remanufacturing, reusing, and recycling within production systems establish closed-loop models that mitigate reliance on finite virgin materials and reduce overall environmental impact. These practices align with the Lean philosophy of maximizing value while minimizing waste. Additionally, [14] suggests that advanced technologies like blockchain-based traceability systems are crucial in enhancing transparency and trust across the supply chain. By ensuring accurate tracking of materials from origin to end-of-life, blockchain facilitates efficient material recovery and reintegration, strengthening circular economy objectives and contributing to more resilient manufacturing ecosystems.

C. Lean-Driven Energy Optimization

Energy management is another critical dimension of Lean Green, encapsulated by Lean-Driven Energy Optimization. This component emphasizes the importance of improving energy efficiency without compromising productivity or product quality. As proposed in [15], the implementation of real-time energy monitoring systems and predictive maintenance strategies enables manufacturers to proactively detect energy inefficiencies, leading to substantial reductions in energy consumption. Additionally, integrating these measures with Lean tools ensures that energy-saving opportunities are identified alongside broader process improvements. Reference [16] further highlights that the adoption of eco-intelligent production systems, which leverage Industry 4.0 technologies such as cyber-physical systems, big data analytics, and machine learning, creates intelligent environments capable of dynamically balancing energy usage according to production demands.

D. Sustainable Raw Material Utilization

The sustainable utilization of raw materials ensures that manufacturing processes prioritize recycled, biodegradable, and renewable resources over traditional, resource-intensive alternatives. This approach not only addresses increasing regulatory and social pressures but also optimizes resource use and reduces the carbon footprint of industrial operations. [12] highlights the growing adoption of biobased materials and additive manufacturing (3D printing) as key strategies to minimize raw material waste and enhance sustainability. These technological innovations enable the creation of customized products with lower input requirements, thereby promoting efficiency and reducing environmental impact. Moreover, [13] argues that applying Lean Green principles in material selection not only decreases environmental impact but also improves cost efficiency and supply chain resilience. Efficient resource use and smart planning help organizations adapt to market changes and support long-term sustainability.

E. Strategic Advances in Efficient Manufacturing in Industry 4.0

[17] identifies fragility factors in Lean Green Manufacturing within Industry 4.0, enabling the analysis of interdependence among human, equipment, and environmental variables to optimize risk management and operational resilience. In this context, [2] highlights how the integration of IoT and Design Intelligence (DID) enhances efficiency, reduces waste, and optimizes processes through predictive maintenance and energy management. The adoption of these technologies promotes proactive resource utilization, minimizing downtime and extending asset life cycles. Similarly, [18] states that optimizing sustainable manufacturing in SMEs through Industry 4.0 requires prioritizing technological and organizational factors, emphasizing IoT and workforce training to maximize operational efficiency and ensure a successful transition toward more competitive and sustainable production models.

F. Digital Transformation and Sustainability Strategies in Manufacturing SMEs

Digital transformation in manufacturing SMEs follows an evolutionary model based on data processing to optimize operational efficiency, supply chain integration, and innovation. The implementation of predictive analytics and digital synchronization facilitates the transition to agile and resilient systems, aligning internal competencies, interorganizational collaboration, and co-creation strategies [19]. Simultaneously, the adoption of green business strategies (GBS) enhances environmental performance through eco-innovation and corporate social responsibility (CSR), reducing waste, energy consumption, and environmental incidents, thereby strengthening sustainability and industrial competitiveness [20]. In this context, the transition to a Circular Economy (CE) requires resource optimization strategies based on the R cycles (recycling, reuse, remanufacturing), driving efficient material management, reverse logistics, and sustainable design to improve regulatory compliance and operational efficiency [21].

3. Methodology

The integration of Lean Green and Smart Manufacturing (LGSM) requires a systematic approach to decision-making, particularly when evaluating strategies for sustainable innovation. The Fuzzy Analytic Hierarchy Process (FAHP) is a robust multi-criteria decision-making (MCDM) methodology that addresses the uncertainty and subjectivity in sustainability assessments by incorporating fuzzy logic into the traditional Analytic Hierarchy Process (AHP) [22]. FAHP enables the structured prioritization of key drivers in sustainable manufacturing ecosystems, such as energy efficiency, waste minimization, automation, and digitalization, by using Triangular Fuzzy Numbers (TFNs) to transform qualitative expert opinions into quantifiable values. This approach helps decision-makers navigate trade-offs between operational efficiency and environmental impact [23]. The following table presents the key drivers of the Lean Green, Smart Manufacturing, and Sustainable Innovation methodologies, each identified as a critical component for improving efficiency and sustainability in manufacturing processes.

Table 1: Key Drivers for Lean Green, Smart Manufacturing, Sustainable Innovation.

Dimension	Abbr.	Drivers	Description
Lean Green	WRP	Waste Reduction in Production	Minimizing waste in manufacturing processes to enhance sustainability and operational efficiency.
	CEI	Circular Economy Integration	Implementing circular economy principles to optimize resource use and reduce environmental impact.
	LDEO	Lean-Driven Energy Optimization	Reducing energy consumption through lean manufacturing and process efficiency improvements.
	SRMU	Sustainable Raw Material Utilization	Prioritizing the use of recycled and eco-friendly raw materials in production processes.
Smart Manufacturing	CPS-S	Cyber-Physical Systems for Sustainability	Implementing interconnected systems for sustainable process automation.
	SPM	Smart Predictive Maintenance	Utilizing digital tools for predictive maintenance to minimize resource wastage and downtime.
	EIMS	Eco-Intelligent Manufacturing Systems	Developing intelligent systems that balance industrial efficiency with environmental responsibility.
	DTT-GM	Digital Twin Technology for Green Manufacturing	Utilizing digital twins to simulate and optimize energy efficiency and sustainability in manufacturing.
	I4.0	Industry 4.0	Reduce costs and improve sustainability in processes
	ANFIS	Adaptive Neuro-Fuzzy Inference System	Improving decision making in production
Sustainable innovation	IoT	Internet of Things	Facilitate the transition to green hydrogen
	AET	Application of eco-efficient technologies	Development of production processes with lower electricity consumption.
	EE	Energy Efficiency	Identify combinations of factors that lead to high sustainable organizational performance
	EP	Environmental practices	Sustainable development
	GIL	Green Inclusive leadership	Employees contribute to environmental sustainability
	EI	Eco – Innovation	In terms of improvements in products, processes and organizational structures.

In this context, the Lean Green, Smart Manufacturing, and Sustainable Innovation framework provides a comprehensive approach to enhancing efficiency, sustainability, and digital transformation in manufacturing. Specifically, Lean Green focuses on waste reduction (WRP), circular economy (CEI), energy optimization (LDEO), and sustainable materials (SRMU) to improve resource efficiency. Meanwhile, Smart Manufacturing integrates cyber-physical systems (CPS-S), predictive maintenance (SPM), eco-intelligent systems (EIMS), digital twins (DTT-GM), Industry 4.0 (I4.0), and adaptive neuro-fuzzy inference (ANFIS) to optimize automation and data-driven decision-making. Finally, Sustainable Innovation promotes IoT for green hydrogen, eco-efficient technologies (AET), environmental practices (EP), green leadership (GIL), and eco-innovation (EI) as key enablers of long-term sustainability and industrial advancement.

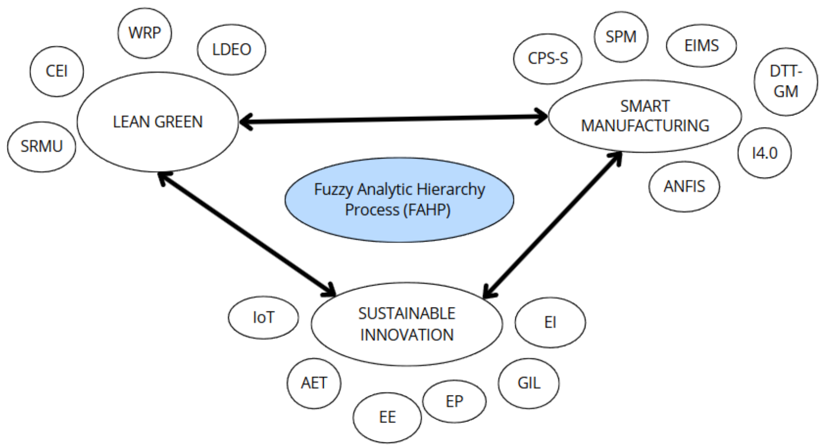

Fig. 1: Theoretical model.

Consequently, a survey has been conducted with seven expert faculty members, each of whom possesses over ten years of experience in the manufacturing industry within the mechanical sector.

4. Results

The analysis of the results obtained from the evaluation of seven experts in the metal-mechanical sector reveals that decision-making is strongly influenced by efficiency and sustainability criteria. Within the Lean Green dimension, waste reduction in production (WRP) emerges as a key driver, reaching a maximum evaluation of 50.15% and averaging 31.21% among experts. Similarly, Lean-based energy optimization (LDEO) is a priority, with a peak value of 38.40% and an average of 27.92%.

In the Smart Manufacturing dimension, advanced technologies significantly impact decision-making. Cyber-Physical Systems for Sustainability (CPS-S) are highly valued, with a relative weight of 39.32%. Additionally, intelligent predictive maintenance (SPM) is another critical driver, registering a weight of 17.99%.

Finally, in the Sustainable Innovation dimension, experts highlight energy efficiency (EE) as a key driver, with values ranging from 8.37% and averaging 17.52%. The Internet of Things (IoT) is also relevant, receiving a score of 10.60%. Overall, the results indicate a strong inclination toward energy optimization and digitalization strategies, prioritizing waste reduction and predictive maintenance over the immediate implementation of more complex emerging technologies.

5. Conclusion

This study demonstrates that the integration of Lean Green and Smart Manufacturing approaches constitutes an effective strategy for addressing sustainability challenges in the metalworking industry, which is characterized by high energy consumption and significant waste generation. Through the application of the Fuzzy Analytic Hierarchy Process (FAHP) and expert evaluations from the sector, Waste Reduction in Production (WRP) emerged as the highest-priority driver, with a weight of 32.4%, followed by Lean-based Energy Optimization (LDEO) at 27.92%. Regarding Smart Manufacturing strategies, Cyber-Physical Systems for Sustainability (CPS-S) and Smart Predictive Maintenance (SPM) stood out with weights of 39.32% and 17.99%, respectively. These findings reflect a clear orientation toward practices that combine operational efficiency, digitalization, and environmental impact mitigation.

The research provides a structured framework that links sustainability priorities with technological enablers, demonstrating that energy efficiency and digital transformation are not only compatible but mutually reinforcing. The use of FAHP strengthens the reliability of the results by incorporating expert judgment under conditions of uncertainty, thereby enhancing strategic decision-making within manufacturing ecosystems. Nevertheless, while the quantitative prioritization of these key drivers offers clarity, it also raises an open question for future research: To what extent can the integration of these prioritized strategies be scaled across different industrial contexts, particularly in small and medium-sized enterprises (SMEs) with limited access to advanced technologies? This question invites further exploration into the implementation challenges and adaptability of such approaches in diverse organizational environments.

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References

[1] Pietka, K., & Bogacz, P. (2024). Lean Green—Integration of Lean Manufacturing and Sustainable Development in the Light of the Pursuit of Economically and Environmentally Efficient Operations. Inżynieria Mineralna, 211(1).
[2] Yang, Z., Wang, Q., & Jia, M. (2023). Integrating Industry 4.0 and the Internet of Things (IoT) for eco-friendly manufacturing. The International Journal of Advanced Manufacturing Technology, 1-10.
[3] Camarinha-Matos, L. M., Rocha, A. D., & Graça, P. (2024). Collaborative approaches in sustainable and resilient manufacturing. Journal of Intelligent Manufacturing, 35, 499–519.
[4] Siegel, R., Antony, J., Govindan, K., Garza-Reyes, J. A., Lameijer, B., & Samadhiya, A. (2024). A framework for the systematic implementation of Green-Lean and sustainability in SMEs. Production Planning & Control, 35(1), 71-89.
[5] Tashkinov, A. G. (2024). The implementation of lean and digital management techniques using artificial intelligence in industrial settings. Discover Artificial Intelligence, 4, 94.
[6] Sarkar, B. D., Shardeo, V., Dwivedi, A., & Pamucar, D. (2024). Digital transition from Industry 4.0 to Industry 5.0 in smart manufacturing: A framework for a sustainable future. Technology in Society, 78, 102649.
[7] Sufian Sufian, A. T., Abdullah, B. M., & Miller, O. J. (2025). Smart Manufacturing Application in Precision Manufacturing. Applied Sciences, 15(2), 915
[8] Jamwal, A., Agrawal, R., & Sharma, M. (2025). Developing a maturity model for Industry 4.0 practices in manufacturing SMEs. Operations Management Research, 1-33.
[9] AbouElaz, M. A., Alhasnawi, B. N., Sedhom, B. E., & Bureš, V. (2025). ANFIS-Optimized Control for Resilient and Efficient Supply Chain Performance in Smart Manufacturing. Results in Engineering, 104262.
[10] Jalil, M. F., Marikan, D. A. B. A., bin Jais, M., & bin Arip, M. A. (2025). Kickstart manufacturing SMEs' go green journey: A green hydrogen acceptance framework to enhance low carbon emissions through green digital technologies. International Journal of Hydrogen Energy, 105, 592-610.
[11] Machingura, T., Adetunji, O., & Maware, C. (2024). The mediatory role of the environmental performance function within the lean-green manufacturing sustainability complex. The TQM Journal.
[12] Abdul Halim-Lim, S., Jamaludin, A. A., Islam, A. T., Weerabahu, S., & Priyono, A. (2025). Unlocking potential for a circular bioeconomy transition through digital innovation, lean manufacturing, and green practices: A review. Management of Environmental Quality: An International Journal, 36(1), 130-154.

[13] Gatell, I. S., & Avella, L. (2024). A maturity model for assessing Digital Green Lean leadership and culture implementation in manufacturing companies. Total Quality Management & Business Excellence, 35(7-8), 860-897.
[14] Kumar, R., & Dvivedi, A. (2024). Prioritizing elements of digitalization for lean and green SME operations: An ISM-MICMAC study in the Indian context. Journal of Advances in Management Research.
[15] Kamna, K. M., Priyamvada, P., Singh, J., & Jaggi, C. K. (2024). A green strategic approach towards a smart production system with promotional and environment-sensitive demand. International Journal of System Assurance Engineering and Management, 15(8), 3672-3687.
[16] Hao, X., Li, Y., Wang, K., Sun, Q., & Wu, H. (2024). Eco-intelligent production: Intelligent manufacturing and industrial green transition. Environment, Development and Sustainability.
[17] Zhu, X., Liang, Y., Xiao, Y., Xiao, G., & Deng, X. (2023). Identification of key brittleness factors for the lean–green manufacturing system in a manufacturing company in the context of industry 4.0, based on the DEMATEL-ISM-MICMAC method. Processes, 11(2), 499.
[18] Sharma, N. K., Kumar, V., Verma, P., Sharma, M., Al Khalil, A., & Daim, T. (2024). Industry 4.0 factors affecting SMEs towards sustainable manufacturing. Technology in Society, 79, 102746.
[19] Zheng, J., Zhang, J. Z., Kamal, M. M., & Mangla, S. K. (2025). A Dual Evolutionary Perspective on the Co-Evolution of Data-Driven Digital Transformation and Value Proposition in Manufacturing SMEs. International Journal of Production Economics, 109561.
[20] Esparza, M. M. G. C. C., Madrid-Guijarro, A., & Maldonado-Guzman, G. (2025). Greening Mexican manufacturing: Examining the role of SMEs in environmental preservation through green business strategies, eco-innovation, and corporate social responsibility. Sustainable Development.
[21] Saari, L., Valkokari, K., Martins, J. T., & Acerbi, F. (2024). Circular economy matrix guiding manufacturing industry companies towards circularity—a multiple case study perspective. Circular Economy and Sustainability, 4(4), 2505-2530.
[22] Shameem, H., & Mittal, R. (2024). A framework for lean tool selection in the label printing industry for sustainable growth. International Journal of System Assurance Engineering and Management.
[23] Oliveira, G. A., Piovesan, G. T., Setti, D., Takechi, S., Tan, K. H., & Tortorella, G. L. (2022). Lean and Green Product Development in SMEs: A Comparative Study between Small- and Medium-Sized Brazilian and Japanese Enterprises. Journal of Open Innovation: Technology, Market, and Complexity, 8(3), 123.