Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management, Orlando, Florida, USA, June 17-19, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250349
Published: June 17, 2025

Evaluating the Impact of Lean 4.0 on Sustainability: An Empirical Study of Performance Outcomes in the U.S. Manufacturing Sector

Maryam Amro
Institute of Research for Technology Development (IR4TD)
University of Kentucky
Lexington, Kentucky, USA

Catherine Maware
Fujio Cho Department of Engineering Technology
University of Kentucky
Lexington, Kentucky, USA

Abstract

This study explores the impact of Lean 4.0, which is an integration of Lean production (LP) and Industry 4.0 (I4.0), on sustainable performance. While existing research has frequently assessed lean and digital technologies in isolation, the combined effect of these approaches remains underexplored. To address this gap, this study aims to evaluate how Lean 4.0 influences sustainability outcomes across economic, environmental, and social dimensions. Structural Equation Modeling (SEM) was used to analyze the relationships between Lean 4.0 implementation and sustainable performance. The data was collected through a structured questionnaire that was distributed to 623 U.S. manufacturing companies, representing a range of industries and sizes, from which 160 valid responses were obtained. The results show that Lean 4.0 significantly improves sustainable performance, highlighting its role as a practical and strategic framework for modern manufacturers. This study contributes empirical evidence to the emerging field of Lean 4.0 and provides guidance for organizations pursuing sustainable industrial transformation through integrated operational strategies.

Keywords
Lean 4.0, sustainable performance, Lean Production (LP), Industry 4.0 (I4.0), Structural Equation Modeling (SEM)

1. Introduction
As the complexity of the manufacturing environment continues to increase, many organizations are seeking ways to reduce waste to remain competitive. As a result of this complexity, the manufacturing sector is now driven by two interconnected philosophies: Lean Production (LP) and Industry 4.0 (I4.0). The LP philosophy, popularized by Womack and Jones in the book The Machine that Changed the World, has been used to minimize waste, increase operational efficiency, and improve quality. On the other hand, the emergence of Industry 4.0 technologies has helped organizations make real-time data-driven decisions.

The concept of Lean 4.0 is now emerging as manufacturing organizations are mandated to improve their sustainability. The Lean 4.0 paradigm combines Industry 4.0 and LP (Kassem et al. 2024). It enhances waste reduction and detection in both digital and physical operations by utilizing digital tools (Romero et al. 2018). Although existing research has tried to analyze the benefits of implementing these philosophies, little is known about how the two strategies work together to affect sustainable results (Rahardjo et al. 2023; Tortorella, Giglio, & Van Dun 2019). Therefore, empirical evidence on Lean 4.0's contribution to sustainable performance remains fragmented (Rossini et al. 2022).

The significance of Lean 4.0 has been a prominent discussion among several researchers (Rahardjo et al. 2023). However, more research is needed since some scientific papers regard LP as a facilitator of Industry 4.0, while others consider it a prerequisite for Industry 4.0 implementation (Buer et al. 2021). This paper adds to the body of knowledge by examining the relationship between Lean 4.0 and sustainable performance in the United States of America. Lean 4.0 is a revolutionary strategy that addresses complex, data-driven challenges and dynamic market demands in manufacturing organizations (Buer et al. 2021). Assessing the impact of Lean 4.0 on manufacturing organizations provides an approach for businesses to enhance social, economic, and environmental sustainability. This research addresses the following question:

How does Lean 4.0 impact the economic, environmental, and social dimensions of sustainability in U.S. manufacturing organizations? The paper is organized as follows: Section 1 is the introduction, Section 2 is the literature review, Sections 3 and 4 are the methodology and results, respectively, and Section 5 is the conclusion.

2. Literature Review

2.1 Lean 4.0

The Lean 4.0 paradigm rose as a competitive need for organizations to enhance their operational performance in modern production systems (Mayr et al. 2018). Lean 4.0 optimizes processes by integrating Lean tools that focus on waste reduction with the advanced technologies of Industry 4.0 (Valamede & Akkari 2020). The LP philosophy was first initiated by the Toyota because it was necessary to be efficient due to resource scarcity after the Second World War in Japan (Valamede & Akkari, 2020). LP ideology aims for continuous improvement by eliminating waste (muda) while maximizing the value for the customer and maintaining quality (Mayr et al. 2018);. Key LP tools include JIT, Kanban, Poka-Yoke, VSM, Kaizen and TPM (Valamede & Akkari 2020). However, traditional LP faced limitations in high-mix, low-volume production and rapid demand fluctuations, highlighting the need for integration with digital technologies.

On the other hand, Industry 4.0 is characterized by its smart capabilities leveraged by Cyber-Physical Systems (CPS), cloud computing, 3D printing, Internet of Things (IoT), Big Data, and AI that enable real-time data exchange, predictive maintenance, and autonomous decision-making (Bueno et al. 2023). The connection between physical and digital worlds is enabled in Industry 4.0 by integrating information and communication technologies (ICT) into manufacturing systems where digitized, intelligent, and interconnected production environments communicate and self-organize machines, products, and systems (Ejsmont et al. 2020). A classic example of how I4.0 shifts manufacturing from centralized control to decentralization and autonomy is when machines in smart factories optimize themselves (Valamede & Akkari 2020). Yet, Industry 4.0 is constrained by the risk of automating waste if it is not aided by the efficiency foundation of LP (Mayr et al. 2018).

Over time, Naciri et al. (2022) explained how Lean has grown and expanded along with the development of manufacturing and its growing complexity. LP was broadly considered a toolbox for operational efficiency based on 5S, Kaizen, Total Productive Maintenance (TPM), etc. Lean 2.0 took a system-wide view as production systems matured and adopted tools like Value Stream Mapping (VSM), Single-Minute Exchange of Dies (SMED), Kanban, and Heijunka to balance workloads and reduce setup times. Later on, the need for strategic alignment brought Hoshin Kanri to synchronize improvement efforts with organizational goals. With the advent of digital technologies, Lean 4.0 has emerged, also known as Smart Lean or Lean automation, which looks to marry LP with Industry 4.0 technologies. In this way, several views have been presented by various scholars: some claim Lean precedes digital transformation, others contend that Industry 4.0 makes up for Lean's shortfalls in flexibility and complexity, while the third perspective places these two paradigms as complementary and mutually reinforcing. In any case, from all perspectives, the core of Lean remains unchanged and has been modernized with the arrival of technologies such as real-time data analytics for dynamic and responsive production systems (Naciri et al.2022).

The Lean 4.0 paradigm continues transforming manufacturing by improving data visibility and analysis, enhancing decision-making, and increasing efficiency (Javaid et al. 2022). Mayr et al. (2018) and Valamede and Akkari (2020) introduce the transformation of traditional Lean tools into Lean 4.0 tools, integrating digital technologies to improve responsiveness in manufacturing environments. Traditionally, LP relied on manual tools such as Value stream maps, pull systems, takt time, 5S, kanban, and other tools to analyze waste. Thus, LP relied heavily on human intelligence, expertise, and manual interventions (Miqueo, Torralba, & Yagüe-Fabra, 2020; Powell, 2024). Process improvements depended on team-driven Kaizen blitz, quality circles, and cross-functional teams. However, as many manufacturing organizations have more access to digital technologies, more processes are now automatic, monitored, and optimized by industry 4.0 technologies, such as IoT, AI, machine learning, Virtual Reality, Additive manufacturing, augmented reality, Digital twin, Autonomous robots, and cyber-physical systems. As a result, AI insights have aided humans in making decisions on the shop floor, and decision-making has also expanded to the supply chain (Belhadi et al. 2022; Wu, Liu, & Liang 2024). JIT 4.0 uses cloud platforms to automate material delivery and predict demand, while TPM 4.0 uses IoT sensors and Augumented Reality for predictive maintenance. Poka-Yoke is enhanced with computer vision and Radio-Frequency Identification (RFID) technologies to prevent assembly errors in real-time. Lean 4.0 also strengthens Kaizen practices with AI and digital twins, and uses smartwatches and AI to classify issues and notify teams.

Utilizing the I4.0 techniques has made identifying waste in real time easier (Wassan & Kalwar 2025), thus enhancing the quick problem-solving process on the production floor (Nedjwa, Bertrand, & Sassi Boudemagh 2022). As a result, waste such as overproduction and downtime is reduced through machine learning (Garre, Ruiz, & Hontoria 2020) that supports demand forecasting and predictive maintenance (Shahin et al. 2023), respectively. Lean 4.0 has also enabled end-to-end visibility of supply chain partners such as suppliers, manufacturers, distributors, and customers. Traditionally, waste identification happened in the four walls of an organization, and Lean 4.0 has made problem-solving efforts to span across the supply chain. It thus becomes easier to scale Lean initiatives, standardized digital tools, and problem-solving efforts via cloud platforms than traditional Lean, which requires more hands-on application and physical presence. It is also easier for various departments, such as production, design, suppliers, logistics, and customer service, to collaborate seamlessly to solve problems as information is quickly shared among various groups. Automated learning and process adaptability make digital data collection and analysis easier than traditional Lean, which uses manual checklists and inspection tools. Worker empowerment is enhanced through augmented reality (Hannola et al. 2018), digital work instructions, and mobile applications, enabling the easy identification of abnormalities. Lean 4.0, therefore, improves quality, flexibility, customization, and predictive capabilities.

Critical success factors for Lean 4.0 implementation were identified in a systematic literature review done by Bueno et al. (2023), claiming that LP should be applied first to balance the complexity and understand the process. Another factor includes developing a continuous improvement culture and changing employee mindsets toward innovation and digitalization. Proper alignment of technology and simplicity, cross-functional collaboration, and process reengineering are also essential. However, Bueno et al. (2023) also mention that Lean 4.0 faces many barriers, including the contrasting focuses of LP and Industry 4.0, the lack of skilled workers with high initial costs, the lack of proof and justification with successful cases, and insufficient institutional support. Despite all of these challenges, Lean 4.0 is worth implementing due to several benefits identified by Bueno et al. (2023) in 4 different areas, including operational performance benefits shown by faster defect detection and productivity gains. Also, financial performance benefits by reducing downtime costs, in addition to AI-powered hazard alerts for safety benefits, and smart wearables to reduce manual work for human-centric benefits. Together, these elements underline the transformative potential of Lean 4.0 when strategic alignment and support mechanisms are in place.

2.2 Hypothesis Formulation

This section explains how the structural model was developed to assess Lean 4.0's impact on sustainable performance and how the factors and items relate, as shown in Figure 1 below. The study hypothesizes (H1) that Lean 4.0 has a significant and positive impact on sustainable performance. The section that follows will explain each of the constructs that make up the research model.

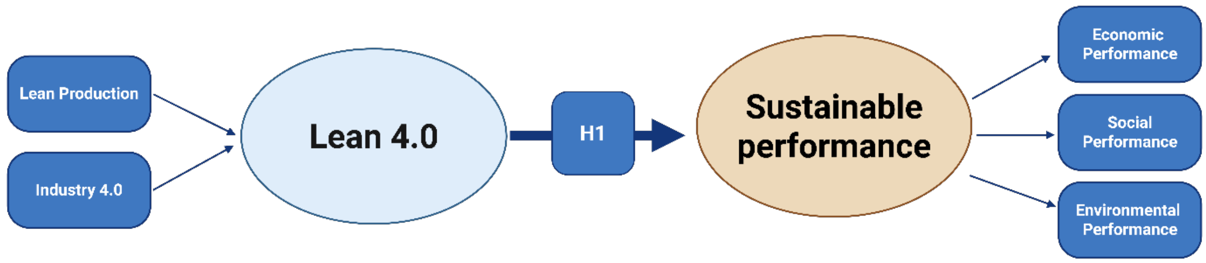

Figure 1. Research model

2.3 Lean production construct

LP is a multidimensional system encompassing the supplier, the customer, and internal practices (Shah & Ward 2007). In order to understand how to implement Lean practices, a comprehensive framework of 10 factors can be categorized into four groups: Supplier factors, Customer factors, Process factors, Control and human factors (Ejsmont et al.2020).

2.3.1 Supplier factors

The supplier factor focuses on finding methods to integrate business with suppliers while managing the flow of goods and information between the supplier and the organization (Maware & Parsley, 2023). Three critical dimensions are included in the supplier factors which are supplier feedback, just-in-time (JIT) delivery, and supplier development (Kamble, Gunasekaran, & Dhone, 2020). Waste frequently results from poor communication between suppliers and manufacturers; therefore, Industry 4.0 technologies like cloud computing and mobile integration allow for improved collaboration and real-time, automated feedback (Sanders, Elangeswaran, & Wulfsberg,2016). The supplier feedback dimension is to provide constant feedback about the performance of the suppliers from a quality and delivery perspective, to build a long-term strategic relationship (Onwughalu, Okeke, & Henry-Chibor, 2017) while making sure that the information is transferred appropriately to avoid waste (Sanders, Elangeswaran, & Wulfsberg, 2016).
Just-in-time delivery by suppliers is to deliver only the required quantity at the right time and location (Kamble, Gunasekaran, & Dhone 2020).

This requires synchronized, timely delivery, precise tracking, and quick adjustments, sometimes achieved by a supplier certification program. (Kamble, Gunasekaran, & Dhone 2020; Sanders, Elangeswaran, & Wulfsberg 2016). Analyzing JIT eliminates delays and excess storage by assessing supplier involvement and ensuring minimal variance in desired product time delivery (Ghaithan et al. 2023). Additionally, Supplier development is the strategic process of digging deep and building close working relationships with the key suppliers who are often nearby to match competency levels with the manufacturer. It involves actions such as reducing the supplier base, improving communication systems, enabling suppliers to manage inventories, evaluating total cost rather than unit price, and leveraging Industry 4.0 technologies to share data, knowledge, and resources-in order to align the suppliers' capabilities with LP goals and improve performances mutually (Kamble, Gunasekaran, & Dhone 2020). Integrating LP and industry 4.0 enables RFID, cloud computing, and IoT to enhance production adaptation, facilitate information exchange between customers, manufacturers, and suppliers, and speed up response times through digital performance tables (Ejsmont et al. 2020).

2.3.2 Customer factors

The customer factors construct emphasizes the firm’s customers and their needs, specifically the customers' participation in business processes . Customer involvement focuses on prioritizing customers’ needs so they can be satisfied by engaging them in the early stages of the product development process, so there is no waste in unnecessary features or redesign (Ghaithan et al. 2023). Maintaining close customer relationships and gathering feedback on quality and delivery performance can help reduce variations in demand and improve overall business performance (Kamble, Gunasekaran, & Dhone2020). Industry 4.0 enhances customer involvement through data-driven, dynamic processes, enabling real-time communication and transparency through digital tools and intelligent manufacturing systems, prolonging the impact of input on production (Ejsmont et al.2020; Sanders, Elangeswaran, & Wulfsberg 2016).

2.3.3 Process factors

The Process factor construct is focused on the activities and sequencing of the processes within a firm . Implementing dimensions like pull production, continuous flow, and setup time reduction aims to create a LP system that truly works, focusing on ensuring that raw materials flow smoothly into the transformation process and are efficiently turned into finished goods (Sanders, Elangeswaran, & Wulfsberg 2016; Shah & Ward 2007). Pull production, which is opposite to push production, supports producing what is needed when it is required in the quantity needed. By which operations are driven by actual customer demand rather than forecast, avoiding overproduction and excess inventory (Sanders, Elangeswaran, & Wulfsberg 2016). This facilitate JIT and it usually often implemented via kanban systems (Shah & Ward 2007).

Continuous flow reduces large and significant halts to ensure a smooth, uninterrupted, streamlined flow through the value stream, minimizing waiting, batching, and inventory (Sanders, Elangeswaran, & Wulfsberg, 2016). Continuous flow is quantified by examining the appropriate arrangement of production items, workstations and equipment, and factory layout (Ghaithan et al. 2023). Setup Time Reduction aims to reduce process downtime between product changeovers (Shah & Ward 2007). It focuses on minimizing the time needed to adapt resources for product variations (Kamble, Gunasekaran, & Dhone, 2020). Lean techniques like Single-Minute Exchange of Die (SMED) aim to reduce setup times to under 10 minutes to address the need for fast and efficient changeovers (Sanders, Elangeswaran, & Wulfsberg, 2016). Industry 4.0 technologies like CPS and RFID enable real-time access to operational data, speeding up production management, monitoring details, and communication with machines. They simplify use of e-kanban systems, sensors, embedded devices, and software, and facilitate JIT implementation through IoT (Ejsmont et al. 2020).

2.3.4 Control and human factors

The control and human factor implies controlling staff and systems to maintain high-quality production and foster an engaged workforce. This strives to produce high-quality goods, which comes from effectively combining the well-being of the manufacturing equipment, statistical process control, and the essential role of human involvement (Kamble, Gunasekaran & Dhone 2020). TPM, Statistical Process Control (SPC), and Employee Involvement comprise the control and human factors (Sanders, Elangeswaran, & Wulfsberg 2016). TPM is a core Lean approach designed to enhance equipment efficiency by minimizing downtime through proactive and preventive maintenance (Onwughalu, Okeke, & Henry-Chibor 2017). It involves machines, tools, processes, and employee participation to maintain and improve production and quality systems. By sustaining equipment performance throughout its lifecycle, TPM helps prevent failures, reduce breakdowns and labor disruptions, and support the organization's overall development (Demeter & Matyusz 2011).

SPC supports achieving operational excellence by building a culture of high-quality production, ensuring that the supply units passed to subsequent processes are free from defects (Kamble, Gunasekaran, & Dhone 2020). Utilizing data and statistics to track production floor performance, SPC guarantees more specification-conforming products with less scrap or rework (Ghaithan et al., 2023). Employee involvement is an important human factor that motivates employees to contribute to the development of the company beyond their primary routine roles (Sanders, Elangeswaran, & Wulfsberg, 2016). It emphasizes commitment, participation, education, and responsiveness, and is considered essential for achieving a lean organization (Herzog & Tonchia 2014). Implementing Industry 4.0 technologies in lean control and human dimensions enhances real-time monitoring, predictive maintenance, and autonomous quality control. CPS and smart devices detect failures, trigger service alerts, and track KPIs using analytics. AR, VR, and cloud-based tools improve operator performance, training, and safety by enabling virtual simulations and guided procedures (Ejsmont et al. 2020).

2.4 Industry 4.0 construct

Industry 4.0 enhances the flexibility, productivity, responsiveness, and effectiveness of production systems by a paradigm shift of combining both digital intelligence with the physical systems, focusing on data more than objects (Kamble, Gunasekaran, & Dhone, 2020). The technologies looked into in this regard are cloud computing, big data analytics, the IoT, additive manufacturing, robotic systems, and augmented reality (AR), with each of them acting as a digital contract to enhance lean capabilities and sustainability outcomes. Cloud computing enables a firm to focus on its core operations by having on-demand access to data storage and computing power through outsourcing them (Ghaithan et al., 2021). This helps improve real-time collaboration, communication, and visibility across production and supply chains (Fang, Gao, & Tortorella 2025).

Big data analytics very powerful support to the lean approach since it allows for processing and interpretation of very large datasets to meaningful information, enabling the discovery of patterns, predicting disruptions, and optimizing operations (Rahardjo et al., 2023). Hence, under Lean 4.0, big data analytics becomes key for real-time performance monitoring, quality control, and risk abatement, reducing waste, lowering emissions, and achieving greater operational efficiency (Fang, Gao, & Tortorella, 2025). IoT is considered the backbone of Industry 4.0 smart manufacturing, connecting objects over the internet through sensors and communication networks, offering real-time insights (Ghaithan et al.2021). Additionally, IoT enables the dynamic management of complex systems by facilitating real-time interaction between people, machines, and ICT systems, significantly enhancing adaptability, transparency, and sustainability across operations supporting Lean practices (Buhaya & Metwally 2024).

Additive manufacturing, including 3D printing, is heavily relied on in Industry 4.0 because it simplifies manufacturing, saves money and time, enables quick prototyping, and facilitates highly decentralized production processes (Rahardjo et al. 2023). It enhances process integration by combining material layers to create three-dimensional objects based on digital designs (Ghaithan et al. 2021). Robotic systems are autonomous machines usually used to reduce human error, improve safety, and lower operational costs by performing repetitive tasks accurately and efficiently, improving work execution (Ghaithan et al. 2023). AR keeps a real-time support framework for task execution, training, and maintenance by overlaying digital data onto the real world (Ghaithan et al. 2021). It improves operator performance, reduces errors, and makes knowledge transfer easier in Lean 4.0 (Rahardjo et al. 2023).

2.5 Sustainable performance construct

The manufacturing sector is undergoing a revolutionary change fueled by Lean 4.0. because organizations are seeking potential ways to improve their sustainable performance, also referred to as sustainable organizational performance (Kamble, Gunasekaran, & Dhone, 2020). In order to achieve sustainable organizational performance, manufacturers should prioritize social and environmental considerations in addition to profit maximization (Ooi, Teh, & Cheang, 2023). This comprehensive approach is captured by the Triple Bottom Line (TBL) framework, which was brought to the forefront by Elkington (1998). It assesses an organization's sustainability by looking at three interconnected areas: economic, environmental, and social performance.

Economic sustainability is the primary goal of any organization to maximize the gains for internal stakeholders by increasing revenues and minimizing costs without compromising the environment or social issues (Ooi, Teh, & Cheang, 2023). This guarantees an organization's ability to maintain long-term financial viability and competitiveness, resulting in increased market share, profitability, and ongoing innovation. Social sustainability embodies the organization's humanitarian context, fostering a safe, inclusive, and equitable environment for development employees and communities (Ghaithan et al.2023). It involves considerations such as occupational health and safety, employee well-being, workplace conditions, training, job satisfaction, and fair labor practices (Ghaithan et al. 2021). Environmental sustainability emphasizes manufacturers' responsibility to reduce pollution and generate resources without compromising the needs of future generations, aiming for net zero emissions or a positive environmental footprint (Ooi, Teh, & Cheang 2023). Its measures include reducing industrial waste and energy consumption, promoting a circular economy, and collaborating with partners to reduce environmental business waste, emissions, and energy consumption (Ghaithan et al.2023). Together, Lean 4.0 promotes circular economy practices by promoting smarter resource use, recycling, and emission control, enabling firms to reduce their environmental footprint and meet sustainability expectations.

2.6 The Impact of Lean 4.0 on Sustainable Performance

Lean 4.0 is gaining advantage as a key driver for sustainability. It enables faster, smarter, and more transparent processes, positively impacting economic and environmental performance and promoting social outcomes. However, more empirical validation is needed to fully understand the measurable impacts of Lean 4.0 on sustainability metrics, especially in diverse industrial settings. Several studies show that Lean 4.0 and sustainability performance are positively correlated, providing synergistic benefits that neither Lean nor I4.0 could accomplish on their own. LP plays an important mediating role in this integrated system, enhancing the effects of Industry 4.0 technologies. Digital technology adoption by itself might not result in noticeable or quick sustainability improvements without lean foundations. This is due to the fact that lean offers the culture of continuous improvement and structured procedures required to fully utilize I4.0 capabilities. A study in the Iberian Peninsula found that integrating LP with I4.0 technologies significantly improves sustainability performance, emphasizing the importance of combining digital and lean strategies (Varela et al. 2019). Similarly, an empirical study in Saudi Arabia's industries revealed LP as a full mediator in the relationship between I4.0 technologies and sustainability, emphasizing the importance of LP principles in digital adoption to significantly enhance sustainable performance (Ghaithan et al. 2021). This mediating role of LP was further confirmed by a study that had evidence of sustainability performance improvement in Indian companies (Kamble, Gunasekaran, & Dhone 2020). Additionally, the Egyptian manufacturing study and a Chinese construction study found that lean manufacturing enhances Industry 4.0 technologies' effectiveness and sustainability outcomes, particularly in energy efficiency and social well-being (Fang, Gao, & Tortorella 2025). This study, therefore, hypothesizes (H_1) that Lean 4.0 is positively related to sustanable performance.

3. Method

The researchers conducted the study in the following steps: the first step involved developing the questionnaire, followed by data collection and analysis.

3.1 Questionnaire development

The questionnaire developed by the researchers was used to analyze the relationships between the constructs. A five point scale (1- strongly disagree, 2 - Disagree, 3 - Undecided, 4 - Agree, and 5 - strongly agree) was utilized for items that were used to measure the seven constructs in the framework: LP, I4.0, Lean 4.0, Sustainable performance, social performance, economic performance and environmental performance. These were taken from other studies and therefore had strong psychometric properties. These questions were taken from researchers such as (Kamble, Gunasekaran, & Dhone 2020; Sajan, Shalij, & Ramesh 2017; Shah & Ward 2007). Six professionals in Industrial Engineering examined the questionnaire for suitability, clarity, and ambiguity. The Cronbach alpha (α) values were computed for these items and items that scored less than 0.70 were reworded and modified due to concerns about clarity.

3.2 Data collection

The sample was initially composed of 623 manufacturing companies in the USA, representing a range of industries and company sizes. After data cleaning and validation, 160 usable responses were retained for analysis. The researchers sent a link to the questionnaire via email to 412 manufacturing companies in the United States. Furthermore, 211 questionnaires were given in person to attendees of the LP professional certification. Manufacturing companies were randomly selected from each state to obtain a sample representative of the entire population. The study was conducted voluntarily, and the researchers reminded participants to complete the questionnaire via follow-up messages sent out four and eight weeks later. Only those familiar with Lean 4.0 were asked to complete the survey, according to the cover letter attached to the email.

The sample comprised small businesses (3.64%), medium-sized businesses (10%), and Large Enterprises (86.36%). In reference to the percentage representation by industrial sector, the representation was: Aerospace 20.83, Laboratory consumables 2.08, Food Manufacturing 8.33, Diesel engine manufacturing 14.58, Machinery manufacturing 6.25, Electronics 25.00, Garment manufacturing 2.08, Medical devices manufacturing 10.42, Automotive 4.17, Munitions 6.25. Additionally, 20.47% of the organizations had implemented LP for less than 5 years, 26.55% had implemented LP between 5 – 10 years, 31.46% of the organizations had implemented LP between 10 -20 years, and 21.52% had implemented LP for more than 20 years.

3.3 Data Analysis

By utilizing the IBM SPSS version 29.0.1.0 software, an exploratory factor analysis was conducted on the data to determine weights for the constructs with Varimax rotation and assign scores to latent constructs that are not directly observable. The Kaiser–Meyer–Olkin (KMO) and Bartlett Sphericity tests were used to determine whether the data were suitable for EFA. The dataset's characteristics are considered suitable for Bartlett's Sphericity test significance at the 5% level and KMO test values greater than 05. In this study, the EFA used the Principal Component Analysis approach with Varimax and Kaiser Normalization to extract factors. Retained factors have eigenvalues greater than one, individually accounting for more than 10% of the total variance and collectively helping to explain why they are not directly observable. The relationship between Lean 4.0 and sustainable performance was evaluated using the Structural Equation Modeling model by utilizing SmartPLS4 software.

4. Results and Discussion

4.1 Measurement Model Analysis

First, 57 questions were used to measure the two first-order constructs (sustainable performance and Lean 4.0). Thirty-five (35) questions were utilized in the final analysis after the number was decreased by exploratory factor analysis. When assessing the construct validity, two elements were taken into account: discriminant and convergent validity. To ascertain convergent validity, the principal component analysis looked at the constructs' unidimensionality (Cheah et al. 2018). According to Bartlett's test of sphericity, every factor had p-values less than 0.001, and the Kaiser-Meyer-Olkin measure of sample adequacy was higher than the desired threshold of 0.5. The independent variable items, which were loaded into a single construct and had eigenvalues larger than 1.0, explained more than half of the variance. Additionally, it supported unidimensionality with factor loadings greater than 0.5.

As additional indicators of convergent validity, Average Variance Extracted (AVE) and Composite reliability were calculated. The recommended thresholds for adequate convergent validity are composite reliability > 0.7 and AVE values > 0.5 (Ab Hamid, Sami, & Sidek, 2017). In order to assess discriminant validity, the writers followed the recommendations made by Fornell and Larcker. Discriminant validity was ensured because the factor's AVE values were greater than the square of its bivariate correlations with the other components. In every case, this requirement was satisfied. As a reliability test, the Cronbach's alpha coefficient was calculated. Through a reliability study, the Cronbach's alpha coefficient was established. Since all of the total scores were higher than the recommended cutoff of 0.7 (Forza, 2002), they could be trusted for further study.

4.2 Results for the Structural Model

The researchers' model assessed the impact of Lean 4.0 on sustainable performance. Lean Practices (LP) and Industry 4.0 (I4.0) were antecedents to Lean 4.0, and Sustainable Performance was composed of economic, environmental, and social constructs. The structural model was assessed based on path coefficients, R^2 values, and significance levels obtained via bootstrapping (using 5,000 subsamples).

Table 1. Path coefficients between constructs

	Economic Performance	**Environmental Performance**	**I4.0**	**LP**	**Lean 4.0**	**Social Performance**	**Sustainable Performance**
Economic Performance							**0.894**
Environmental Performance							**0.838**
I4.0					**0.863**		
LP					**0.744**		
Lean 4.0							**0.523**
Social Performance							**0.856**
Sustainable Performance							

The results supported Hypothesis (H_1) since the path from Lean 4.0 to Sustainable Performance was positive (0.523) and statistically significant. The p-value obtained was less than 0.001, indicating that the path was significant. This result indicated that the integration of Lean Practices with Industry 4.0 technologies (Lean 4.0) positively and significantly contributed to the overall sustainable performance of organizations. The R^2 value for Sustainable Performance obtained was 0.46, which was moderate, indicating that Lean 4.0 contributed 46% of the variance in sustainable performance. Similarly, the R^2 value for Lean 4.0 was also ($R^2 = 0.58$), suggesting that LP and I4.0 jointly explained 58% of the variation in the Lean 4.0 construct. The economic, social, and environmental dimensions loaded significantly onto the Sustainable Performance. The path coefficients obtained were: Economic Performance = 0.894, Social Performance = 0.856, and Environmental Performance = 0.838. The findings highlight that organizations adopting Lean 4.0 practices improved sustainability outcomes. This confirmed the synergistic impact of combining LP with Industry 4.0 technologies, driving not only operational efficiency but also long-term sustainable development.

5. Conclusion

This paper contributes to the literature by empirically validating the concept of Lean 4.0, demonstrating its significant impact on sustainable performance using survey data from U.S. manufacturers. It used SEM to analyze the impact of Lean 4.0 on Sustainable performance in the Manufacturing industries in the USA. The results indicated that Lean 4.0 improved sustainable performance in manufacturing organizations. This could be because Industry 4.0 technologies improved decision-making and enhanced waste identification processes, leading to improved performance. The use of Industry 4.0 technologies improved sustainable performance through real-time monitoring, predictive maintenance, workplace safety, and transparent operations. Many manufacturing organizations in the USA have moved beyond traditional efficiency metrics and have made their organizations smarter, cleaner, and more agile. This study contributes to the growing body of knowledge by analyzing and validating the impact of Lean 4.0 on sustainable performance. This study offers insights to industry practitioners seeking to improve the sustainability of organizations by achieving the triple bottom line (people, planet, and profit). Future research can explore the impact of either moderating or mediating variables such as organizational culture, leadership, or digital maturity. Longitudinal studies across different sectors and regions could also help generalize these findings further.

References

Ab Hamid, M. R., Sami, W., & Sidek, M. M., Discriminant validity assessment: Use of Fornell & Larcker criterion versus HTMT criterion, *Journal of physics: Conference series*, vol. 890, No. 1, p. 012163, 2017.

Belhadi, A., Kamble, S., Fosso Wamba, S., & Queiroz, M. M., Building supply-chain resilience: an artificial intelligence-based technique and decision-making framework, *International Journal of Production Research*, vol.60, no.14, pp.4487-4507,2022.

Bueno, A., Caiado, R. G. G., de Oliveira, T. L. G., Scavarda, L. F., Godinho Filho, M., & Tortorella, G. L., Lean 4.0 implementation framework: proposition using a multi-method research approach, *International Journal of Production Economics*, vol. 264, pp. 108988, 2023.

Buer, S.-V., Semini, M., Strandhagen, J. O., & Sgarbossa, F., The complementary effect of lean manufacturing and digitalisation on operational performance, *International Journal of Production Research*, vol. 59,no.7, pp.1976-1992, 2021.

Buhaya, M. I., & Metwally, A. B. M. The interplay between digital technologies and sustainable performance: does lean manufacturing matter?, *Sustainability*, vol.16, no.22, p.10002, 2024.

Cheah, J.-H., Sarstedt, M., Ringle, C. M., Ramayah, T., & Ting, H., Convergent validity assessment of formatively measured constructs in PLS-SEM: On using single-item versus multi-item measures in redundancy analyses, *International journal of contemporary hospitality management*, vol.30, no.11, pp.3192-3210, 2018.

Demeter, K., & Matyusz, Z., The impact of lean practices on inventory turnover, *International Journal of Production Economics*, vol.133, no.1, pp.154-163, 2011.

Ejsmont, K., Gladysz, B., Corti, D., Castaño, F., Mohammed, W. M., & Martinez Lastra, J. L., Towards 'Lean Industry 4.0 ′–Current trends and future perspectives, *Cogent Business & Management*, vol.7, no.1, pp.1781995, 2020.

Elkington, J., Partnerships from cannibals with forks: The triple bottom line of 21st-century business, *Environmental quality management*, vol.8, no.1, pp.37-51, 1998.

Fang, Y., Gao, S., & Tortorella, G., Exploring the use of lean construction ambidexterity and industry 4.0 to achieve sustainable performance. *International Journal of Lean Six Sigma*, 2025.

Forza, C., Survey research in operations management: a process-based perspective. *International journal of operations & production management*, vol.22, no.2, pp.152-194, 2002.

Garre, A., Ruiz, M. C., & Hontoria, E., Application of Machine Learning to support production planning of a food industry in the context of waste generation under uncertainty. *Operations Research Perspectives*, vol.7, p.100147, 2020.

Ghaithan, A., Khan, M., Mohammed, A., & Hadidi, L., Impact of industry 4.0 and lean manufacturing on the sustainability performance of plastic and petrochemical organizations in Saudi Arabia, *Sustainability*, vol.13, no.20, p.11252, 2021.

Ghaithan, A. M., Alshammakhi, Y., Mohammed, A., & Mazher, K. M., Integrated impact of circular economy, industry 4.0, and lean manufacturing on sustainability performance of manufacturing firm, *International journal of environmental research and public health*, vol.20, no.6, p.5119, 2023.

Hannola, L., Richter, A., Richter, S., & Stocker, A., Empowering production workers with digitally facilitated knowledge processes–a conceptual framework, *International Journal of Production Research*, vol.56, no.14, pp.4729-4743, 2018.

Herzog, N. V., & Tonchia, S., An instrument for measuring the degree of lean implementation in manufacturing, *Strojniški vestnik-Journal of Mechanical Engineering*, vol.60, no.12, pp.797-803, 2014.

Javaid, M., Haleem, A., Singh, R. P., Rab, S., Suman, R., & Khan, S., Exploring relationships between Lean 4.0 and manufacturing industry, *Industrial Robot: the international journal of robotics research and application*, vol.49, no.3, pp.402-414, 2022.

Kamble, S., Gunasekaran, A., & Dhone, N. C., Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies, *International journal of production research*, vol.58, no.5, pp.1319-1337, 2020.

Kassem, B., Callupe, M., Rossi, M., Rossini, M., & Portioli-Staudacher, A., Lean 4.0: a systematic literature review on the interaction between lean production and industry 4.0 pillars, *Journal of Manufacturing Technology Management*, vol.35, no.4, pp.821-847, 2024.

Maware, C., & Parsley, D. M., Can industry 4.0 assist lean manufacturing in attaining sustainability over time? Evidence from the US organizations, *Sustainability*, vol.15, no.3, p.1962, 2023.

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., & Franke, J., Lean 4.0-A conceptual conjunction of lean management and Industry 4.0, *Procedia Cirp*, vol.72, pp.622-628, 2018.

Miqueo, A., Torralba, M., & Yagüe-Fabra, J. A., Lean manual assembly 4.0: A systematic review, *Applied Sciences*, vol.10, no.23, p.8555, 2020.

Naciri, L., Mouhib, Z., Gallab, M., Nali, M., Abbou, R., & Kebe, A., Lean and industry 4.0: A leading harmony, *Procedia Computer Science*, vol.200, pp.394-406, 2022.

Nedjwa, E., Bertrand, R., & Sassi Boudemagh, S., Impacts of Industry 4.0 technologies on Lean management tools: a bibliometric analysis, *International Journal on Interactive Design and Manufacturing (IJIDeM)*, pp.1-16, 2022.

Onwughalu, O., Okeke, K., & Henry-Chibor, E., Lean production and its effect in organizations: A study of selected manufacturing firms in Nigeria, *Scholarly Journal of Science Research and Essay*, vol.6, no.4, pp.85-98, 2017.

Ooi, L. L., Teh, S. Y., & Cheang, P. Y. S., The impact of lean production on sustainable organizational performance: the moderating effect of industry 4.0 technologies adoption, *Management Research Review*, vol.46, no.12, pp.1802-1836, 2023.

Powell, D. J., Artificial intelligence in lean manufacturing: digitalization with a human touch?, *International Journal of Lean Six Sigma*, vol.15, no.3, pp.719-729, 2024.

Rahardjo, B., Wang, F.-K., Yeh, R.-H., & Chen, Y.-P., Lean manufacturing in industry 4.0: a smart and sustainable manufacturing system, *Machines*, vol.11, no.1, p.72, 2023.

Romero, D., Gaiardelli, P., Powell, D., Wuest, T., & Thürer, M., Digital lean cyber-physical production systems: the emergence of digital lean manufacturing and the significance of digital waste. Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing: IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, Proceedings, Part I, , August 26-30, 2018.

Rossini, M., Costa, F., Tortorella, G. L., Valvo, A., & Portioli-Staudacher, A., Lean Production and Industry 4.0 integration: how Lean Automation is emerging in manufacturing industry, *International Journal of Production Research*, vol.60, no.21, pp.6430-6450, 2022.

Sajan, M., Shalij, P., & Ramesh, A., Lean manufacturing practices in Indian manufacturing SMEs and their effect on sustainability performance, *Journal of Manufacturing Technology Management*, vol.28, no.6, pp.772-793, 2017.

Sanders, A., Elangeswaran, C., & Wulfsberg, J., Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing, *Journal of industrial engineering and management*, vol.9, no.3, pp.811-833, 2016.

Shah, R., & Ward, P. T., Defining and developing measures of lean production, *Journal of operations management*, vol.25, no.4, pp.785-805, 2007.

Shahin, M., Chen, F. F., Hosseinzadeh, A., & Zand, N., Using machine learning and deep learning algorithms for downtime minimization in manufacturing systems: An early failure detection diagnostic service, *The International Journal of Advanced Manufacturing Technology*, vol.128, no.9, pp.3857-3883, 2023.

Tortorella, G. L., Giglio, R., & Van Dun, D. H., Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement, *International journal of operations & production management*, vol.39, no.6/7/8, pp.860-886, 2019.

Valamede, L. S., & Akkari, A. C. S., Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies, *International Journal of Mathematical, Engineering and Management Sciences*, vol.5, no.5, p.851, 2020.

Varela, L., Araújo, A., Ávila, P., Castro, H., & Putnik, G., Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability, *Sustainability*, vol.11, no.5, p.1439, 2019.

Wassan, A. N., & Kalwar, M. A., The Role of Logistics 4.0 and Industry 4.0 in Promoting Sustainable Operations and Performance, *Jordan Journal of Mechanical & Industrial Engineering*, vol.19, no.1,2025.

Wu, H., Liu, J., & Liang, B., AI-driven supply chain transformation in Industry 5.0: Enhancing resilience and sustainability, *Journal of the Knowledge Economy*, pp.1-43, 2024.