

Article

Can Industry 4.0 Assist Lean Manufacturing in Attaining Sustainability over Time? Evidence from the US Organizations

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Abstract: Recent research asserts that Industry 4.0 technologies have positively impacted Lean Manufacturing and sustainable performance. Although the combined impact of Industry 4.0 and Lean Manufacturing on sustainable performance has been scientifically studied, no study has shown how Lean duration moderates the relationship between Industry 4.0 and Lean Manufacturing in US manufacturing firms. This research aims to close this gap by evaluating whether Lean duration moderates the association between Industry 4.0 and Lean Manufacturing, which in turn affects sustainability performance. The Structural Equation Modeling (SEM) method was used to formulate and examine proposed relationships. The study used data collected from 126 managers who worked in 65 different manufacturing organizations. The data demonstrated a moderating effect of Lean duration on the relationship between Industry 4.0 and Lean Manufacturing and a significant and direct effect of Lean Manufacturing on sustainable performance. However, Industry 4.0 had a positive indirect effect on sustainable performance through the moderating effect of Lean Manufacturing and a negative direct impact on sustainable performance. The study's findings add to the body of knowledge on the impact of Industry 4.0 on the Lean Manufacturing philosophy by identifying Lean duration as a moderator of this relationship. Theoretically, this research empirically validated the association between Lean duration, Industry 4.0, Lean Manufacturing, and sustainable performance in US Manufacturing organizations. The results showed that industry practitioners should consider the effect of Lean duration when adopting and managing Industry 4.0 technologies for better sustainable performance.

Keywords: Industry 4.0; Lean Manufacturing; sustainable performance; Lean duration



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1. Introduction

Organizations are encouraged to improve sustainability due to pressure exerted by the government, non-governmental organizations, and the public. As a result, sustainable manufacturing has become essential, considering the role of the manufacturing industries in society. Many organizations now consider using sustainable manufacturing practices to lower the negative impact on the environment [1], reduce production costs [2], and lower energy and resource consumption [3], thus improving economic, environmental, and social performance [4]. The two methodologies manufacturing industries adopt to improve sustainability include Lean Manufacturing (LM) and Industry 4.0 technologies.

The Lean Manufacturing philosophy focuses on reducing waste and non-value-added activities that do not create value for the customer [5]. Organizations that adopt this philosophy have managed to improve productivity, product quality [6], profitability, and competitiveness [7]. However, research shows that many organizations have difficulties sustaining LM [8–12]. Some challenges organizations face in sustaining this philosophy can be addressed using Industry 4.0 technologies [4]. For example, in places where LM practices are challenging to implement, incorporating Industry 4.0 technologies delivers significant cost savings.

The LM philosophy also emphasizes a production leveling approach, which is incompatible with product customization now demanded by consumers [13]. Thus, the limitation of changeability in the production lines and numerous adjustments in production methods and cycle times make the LM practices unsuitable for customized goods and short product life cycles [14]. Integrating Industry 4.0 technologies into the existing LM framework improves organizational flexibility [15] and enhances the maturation of LM [16]; thus, Industry 4.0 does not replace LM philosophy. In addition, Industry 4.0 technologies provide seamlessly integrated solutions that correspond with an organization's LM thinking aims. Industry 4.0, synonymously known as intelligent and smart manufacturing [17], uses automated, digital, and smart systems to ensure the effectiveness of physical operations and smooth information flow among supply chain patterners [18].

Literature shows the association between Industry 4.0 and LM and how they impact organizational performance. Some researchers suggest that LM mediates the association between Industry 4.0 and organizational performance [4,19–21]. Others show that Industry 4.0 acts as a mediating variable on the relationship between LM and operational performance [22–25], and some indicate that Industry 4.0 moderates the connection between LM and organizational performance [26]. At the same time, some researchers illustrate the direct effect of LM and Industry 4.0 on organizational performance without showing any relationships between these two methodologies [27]. Buer, Semini [28] revealed a complementary effect of LM and Industry 4.0 on operational performance.

Although adopting Industry 4.0 has been shown to accelerate the establishment of LM in organizations, the effect of LM on sustainable operations may be observable after a long period. Organizations may get substantial operational performance improvements after adopting LM for an extended period. Therefore, companies seeking to improve their operations continuously will sustain these benefits. Researchers such as Wickramasinghe and Wickramasinghe [29] and Womack and Jones [30] highlighted the importance of Lean implementation duration when evaluating the impact of LM on operational performance. These researchers stated that LM should not be viewed as a solution for resolving immediate challenges but should be taken as a long-term strategy for eliminating waste. Lean duration refers to the length of time an organization has applied LM [31]. Organizations may have variations in operational performance due to the Lean adoption timeframe [32]. Therefore, this study highlights that Lean duration moderates the relationship between Industry 4.0 and LM. Focusing on the Lean duration attribute allows researchers to explore a company's capacity to continue developing a Lean system over time. Thus, Lean duration captures the longevity and strength of a company's Lean system.

A literature study revealed the disagreements among scholars on the effect of LM and Industry 4.0 on sustainable performance. Some studies show an enabling impact of Industry 4.0 on LM but do not show how Lean duration impacts this relationship. Only one study by Rosin, Forget [27] has shown how the degree of Lean adoption affects Industry 4.0 implementation. However, the research only categorized companies into high or low Lean adopters and did not show how Lean duration impacts that relationship. The objective of this study is to assess the impact of Industry 4.0 on LM and sustainable performance, as well as the moderating role of Lean duration in the relationship between Industry 4.0 and LM. According to the authors' knowledge, this is the first study investigating the moderating effect of Lean duration on the association between Industry 4.0 and LM. This study uses emerging literature on LM, Industry 4.0, and sustainable performance to develop a model that analyzes the moderating effect of Lean duration on the association between Industry 4.0 and LM. This study answers the following questions:

1. How do Industry 4.0 and LM impact sustainable performance?
2. How does Lean duration moderate the relationship between Industry 4.0 and LM?

This research is organized as follows, Section 1 describes the background of the problem, and Section 2 explains the emerging literature on LM, Industry 4.0, Lean duration, and sustainable performance. Next, Section 3 illustrates the methodology employed in

conducting the study, and Section 4 describes the results obtained from the study. Finally, Sections 5 and 6 highlight the discussion and conclusion, respectively.

2. Literature Review

2.1. Industry 4.0 Adoption in Manufacturing Industries

The Federal Government of Germany introduced the term Industry 4.0 in 2011 [33]. Industry 4.0 places a great emphasis on smart technologies and cyber-physical systems [34] that control equipment, industrial plants, and business systems to convey information autonomously, initiate activities, make judgments and influence each other [35]. Its adoption improves the customization of products [36], efficiency [37], agility, and supply chain integration [38], and reduced lead time [39]. Industry 4.0 technologies are used for three primary purposes in manufacturing organizations: (i) production floor management, (ii) data management, and (iii) Information Technology (IT) integration. Table 1 describes the three main application areas and specific Industry 4.0 technologies for each category.

Table 1. Industry 4.0 technologies.

Purpose	Description	Industry 4.0 Technologies
1. Production floor management	Utilizing Industry 4.0 technologies enable mass customization and help in asset maintenance, tracking, and optimization.	Internet of Things (IoT), Additive Manufacturing, Robotic Systems, and Virtual Reality.
2. Data Management	The data generated by machinery and embedded sensors can be analyzed to examine process-based trends, which assist in making informed judgments.	Cloud computing, Big Data Analytics, and IoT.
3. IT integration	The interconnectivity within a smart factory enables vertical and horizontal integration, thus creating an automated value chain.	Cyber-Physical Systems (CPS) and Cyber Security Systems (CSS).

Cyber-Physical Systems incorporate physical and cyber elements and uses sensors, controllers, network, and computing technologies to allow interaction within the production system [40–42]. The IoT technique allows physical entities and virtual personalities to be interconnected, sharing information at any time with anyone/anything at any place using any pathway [43,44]. Thus, the machines on the shop floor are installed with sensors and can connect with other equipment via the web or the internet. The hyperconnectivity between physical entities and virtual entities produces vast amounts of data (Big Data). Cloud computing enables data storage on remote servers [45]. Additive Manufacturing is a process of developing solid objects without human assistance by utilizing computer-generated models [46]. Robotic systems interact with people to perform complicated and unsafe work with high precision [47]. This improves the autonomy, safety, and flexibility of production processes.

2.2. LM Implementation in Manufacturing Industries

LM adoption in various industries has existed for over 40 years, and organizations are implementing diverse practices to reduce all types of waste by identifying non-value-added activities, optimizing processes, and establishing standardized procedures. LM practices have been categorized into four practice bundles: supplier elements, customer elements, process elements, and control and human elements [4,47,48]. Table 2 defines Lean bundles, associated Lean practices, and the authors who mentioned them.

Table 2. LM bundles and practices.

Lean Bundles	Definition	Lean Practices	Authors
Supplier elements	It is focused on ways to integrate with the company's suppliers.	Supplier feedback, supplier development, and Just In Time (JIT) deliveries by suppliers	Godinho Filho, Ganga [49], Herzog and Tonchia [50], Kamble, Gunasekaran [4]
Customer elements	It emphasizes customer participation in company processes.	Customer involvement, customer feedback, and customer suggestion in product development	Alsmadi, Almani [51], Negrão, Godinho Filho [52], Shah and Ward [48]
Process elements	It is concerned with the processes' activities and sequencing.	Pull, continuous flow, and setup time reduction	Kim [53], Bai, Satir [54], Sajan, Shalij [55]
Human and control elements	It involves managing and controlling systems and personnel.	Statistical Process Control (SPC), employee involvement, and TPM	Sanders, Elangeswaran [47], Campos and Vazquez-Brust [56], Onwughalu, Okeke [57], Demeter and Matyusz [58]

2.3. Interoperational Ability between Industry 4.0 and LM

Industry 4.0 can work together with LM without one philosophy replacing the other. Industry 4.0 and LM are not mutually exclusive concepts; instead, they complement one other and help organizations mature their LM techniques [16]. When Industry 4.0 and LM are combined, they have a far more significant synergistic performance impact than if used separately [59]. Industry 4.0 can optimize production processes, lower non-value-added activities, detect abnormalities, and reduce employee workload. In addition, industry 4.0 provides technology support for effective and excellent LM deployment [47].

In Industry 4.0, sensor utilization can do more than identify errors but predict problems and track production processes, improving machine uptime. For example, CPS enhances JIT manufacturing through automatic communication of material requirements, resource usage, and material allocation, thus reducing stockpiling. Wagner, Herrmann [21] named it Cyber-Physical JIT delivery which allows raw materials to move directly from warehouses to the shop floor, thus eliminating the need for buffer stock. The CPS also improves production processes' traceability, predictability, and reliability since sensors track material movement. Therefore, automatic restocking can be possible [60]. CPS also improves Jidoka "autonomation with a human touch" [61]. The human-machine interfaces developed through CPS allow information sharing, collaborative decision-making, and mutual learning. For example, a company that uses Kanban cards to coordinate and monitor can digitize that system using CPS. In addition, using user interfaces that manage information flow and update customer demand improves production leveling.

IoT allows humans and machines to communicate and share data in real-time [62] by providing advanced connections between systems, physical entities, and services, thus optimizing production processes, which improves flexibility [63] and reduces cost and lead time [64]. IoT uses information technology to integrate business operations and engineering functions, which makes production processes efficient. Data generated from LM tools is enormous and involves material quantity, number of employees or machines used, production time, and the overall equipment effectiveness. IoT integration helps the management make a proper real-time decision, enhancing the efficacy of LM [15]. Anosike, Alafropatis [65] found that combining LM and IoT leads to improved decision-making, information flow, response, and production rate.

Lean Manufacturing's goal of eliminating tasks that do not create value for consumers can be improved with additive manufacturing [66]. For example, the lack of geometry restrictions [67] and the decrease in waste caused by workpiece material removal, which are characteristics of conventional machining, are just two of the many opportunities that Additive Manufacturing presents [68]. The Additive Manufacturing production method

only uses the precise quantity of material required and overlays many layers [69,70]. Since the whole manufacturing process takes place inside the 3D printer, there is no need for part warehousing, and raw materials are the only basis of inventory [71,72]. One more illustration is the waste that results from component and material movements that are unavoidable in a production line [71]. The supply chain is substantially shorter in Additive Manufacturing, which reduces transportation waste. As a result of all the benefits Additive Manufacturing offers during the product development process, it can drastically cut down on waiting times and eliminates the need for machine setup periods to adapt to the production of various parts [73]. The ability to make single products in batches is a crucial benefit of AM. Table 3 highlights studies investigating the relationship between LM, Industry 4.0, and sustainable performance.

Table 3. Studies that investigated the relationship between LM, Industry 4.0, and Sustainable performance.

Author	Study	Lean Dimensions	Industry 4.0 Dimensions	Research Methodology Adopted	Results
1. Ciano, Dallasega [74]	Assessment of the association between Lean practices and Industry 4.0 technologies in eight manufacturing organizations	Shop floor management, manufacturing equipment and processes, customer relationships, supplier relationships, new product development, and workforce management.	Simulation, vertical and horizontal systems integration, Internet of Things (IoT), Augmented Reality (AR), cybersecurity, Additive Manufacturing, and Big Data Analytics.	(1) 8 case studies. (2) Face-to-face semi-structured interviews. (3) Company documents, annual reports, and websites. (4) Qualitative analysis	A framework was developed that showed the effect of Lean Manufacturing on Industry 4.0 and the impact of Industry 4.0 on Lean Manufacturing.
2. Rosin, Forget [27]	Analysis of the connections between Industry 4.0 techniques and Lean Manufacturing philosophy, focusing on how Industry 4.0 techniques increase the application of Lean practices.	Problem-solving, continuous flow, 5 Whys, pull systems, genichi genbutsu, quick changeover, JIT, jidoka, employee involvement, cross training, andon, Root Cause Analysis (RCA), error proofing and SPC	CPS, simulation, collaborative robots, cybersecurity, AR, horizontal and vertical systems, and big data.	Qualitative analysis-co-occurrences matrix	The study results demonstrated that Industry 4.0 supported Just-In-Time and Jidoka practices with little to no support for People and Teamwork and waste reduction practices.
3. Chiarini, Belvedere [33]	An analysis of how Industry 4.0 technologies can be used to achieve strategic manufacturing goals.	-	Automated Guided Vehicles (AGV), Big data analytics, 3D printing, IoT, Robotics, and Cloud Computing.	(1) Qualitative research-questionnaire survey (2) One sample test	The use of Industry 4.0 technologies can enhance leanness in manufacturing organizations.
4. Tortorella and Fettermann [22]	An investigation of the impact of Lean tools on Industry 4.0 technologies implementation and their impact on operational performance.	Supplier feedback, JIT delivery, developing suppliers, involved customers, Pull, Flow, Low setup, Controlled processes, Involved employees, Productive maintenance	Additive manufacturing, IOT, simulation, cloud computing and Big Data.	(1) Questionnaire survey (2) Clustering analysis (3) ANOVA (4) Chi-square	Lean tools positively impacted Industry 4.0 technologies, which improved operational performance.
5. Sanders, Elangeswaran [47]	Development of a framework that illustrates how Industry 4.0 can help overcome barriers to LM implementation.	Supplier feedback, JIT delivery by suppliers, Supplier development, Customer involvement, Pull production, Continuous flow, Setup time reduction, Total productive maintenance, Statistical process control, Employee involvement	Cloud computing, IoT, Big data, Radio Frequency Identification (RFID) and CPS	Literature review	A framework was developed that showed the Industry 4.0 technologies that could be used to overcome Lean dimensions identified by literature.
6. Pereira and Sachidananda [75]	An analysis of the association between Industry 4.0 and LM and the impact of these philosophies on operational performance.	Supplier development, customer feedback, predictive maintenance, and JIT	Robotic systems, artificial intelligence, AR, cloud computing and RFID	(1) Questionnaire survey (2) ANOVA (3) One sample T-test	Industry 4.0 positively impacted LM and operational performance.

Table 3. Cont.

Author	Study	Lean Dimensions	Industry 4.0 Dimensions	Research Methodology Adopted	Results
7. Ghaithan, Khan [76]	An evaluation of the effect of Industry 4.0 and LM on economic, social and environmental performance in Saudi Arabian plastic and petrochemical industries.	Supplier feedback, JIT delivery by Suppliers, Supplier development, Customer involvement, Pull production, Continuous flow, Setup time reduction, Total productive maintenance, Statistical process control, Employee involvement	Cloud Computing, IoT, Augmented Reality, Big Data Analysis, Robotic Systems, and Additive Manufacturing	(1) Questionnaire survey (2) Structural Equation Modeling (SEM)	Industry 4.0 and LM have a positive and direct impact on economic, social, and environmental performance.
8. Shahin, Chen [13]	Development of a cloud-based Kanban to assist managers in making effective decisions that enable continuous improvement	Kanban	Cloud computing	Simulation	The cloud-based kanban system enabled managers to make a decision on scheduling times, quality requirements, production rates, performance indicators, and customer support.
9. Dombrowski, Richter [77]	Assessment of the interrelationships between Lean Manufacturing and Industry 4.0 technologies for 260 case scenarios in German	Standardization, visual management, continuous improvement, and pull	Big data, cloud computing, Virtual Reality, RFID, and AR.	(1) Literature review (2) Case studies	The graphs showed the interrelationships between industry technologies and Lean Manufacturing principles and Industry 4.0 characteristics and Lean principles.
10. Satoglu, Ustundag [78]	An analysis of how Industry 4.0 can function as enabling element for the adoption of LM	Cellular Manufacturing, setup reduction, quality control, TPM, production smoothing, Jidoka, supplier development, and Kanban	Cloud computing, Additive Manufacturing, data analytics, AR, IoT, simulation, and virtualization	Literature review	The problems caused by poor management or disorganization cannot be solved by Industry 4.0 technologies alone; thus, an efficient information flow is essential before and after introducing I4.0 technology.
11. Wagner, Herrmann [21]	The creation of a Lean-Industry 4.0 matrix that utilizes Cyber Physical JIT systems in automotive industry project leaders.	JIT and Kanban	CPS, RFID, and data analytics	Simulation	A cyber-physical Just-in-Time delivery system was developed that used a correlation matrix to find Industry 4.0 and LM solutions
12. Ma, Wang [79]	The development of a smart Lean automation engine made possible using CPS technologies (SLAE-CPS) for examining Jidoka functions	Jidoka	IoT, AGV, Robots, RFID, CPS, and cloud computing	(1) Case study (2) Simulation (3) Laboratory experiments	The smart Lean automation engine developed was used and tested on a car company's engine assembly line to handle the assembly of connecting rod bearing shells and main bearing shells, and it proved to be successful.
13. Dave, Kubler [80]	The development of a Lean construction management system framework by integrating IoT standards to improve the communication network in a construction project.	Last Planner system	Cloud computing and IoT	(1) Framework development (2) Prototype development	The developed architecture improved the flow of information and closed the data flow loop for both the site office and the head office.
14. Chen and Chen [81]	The development of a real-time VSM in disc assembly production by wireless monitoring and RFID technology.	VSM, 5 Whys, and Kaizen events	RFID	VSM	The real-time VSM system developed effectively tracked the material flow, thus increasing visibility and improving time management.

Table 3. Cont.

Author	Study	Lean Dimensions	Industry 4.0 Dimensions	Research Methodology Adopted	Results
15. Buer, Semini [28]	An investigation of the relationships between industrial digitalization and LM and the effects each has on organizational performance.	Employee involvement, pull, TPM, continuous flow, SPC, and setup time reduction	IoT, CPS, and cloud computing	(1) Questionnaire survey (2) Hierarchical multiple regression	Lean manufacturing techniques and factory digitalization were both highly effective positive predictors of the level of operational success.
16. Kamble, Gunasekaran [4]	Validation of a direct and indirect effect of Industry 4.0 on LM and Sustainable performance.	Supplier feedback, JIT delivery by suppliers, Supplier development, Customer involvement, Pull production, Continuous flow, Setup time reduction, Total productive maintenance, Statistical process control, Employee involvement	Cloud Computing, IoT, Augmented Reality, Big Data Analysis, Robotic Systems, and Additive Manufacturing	(1) Questionnaire survey (2) Structural Equation Modeling (SEM)	The data supported the existence of LM as a mediating variable in the relationship between Industry 4.0 and sustainable operational performance implying the significant indirect and direct of Industry 4.0 on Sustainable Operational Performance.
17. Lai, Wong [82]	The analysis of the effect of Industry 4.0 techniques on the seven wastes.	JIT, predictive maintenance, and Kanban	AR, CPS and Virtual Reality.	Literature review	Industry 4.0 techniques can enhance the impact of Lean Manufacturing projects and boost productivity.
18. Pagliosa, Tortorella [83]	An exploration of the connections between LM techniques and Industry 4.0 technology.	Kanban, VSM, poka yoke, kaizen, pull, andon, SMED, standardization, TQM, heijunka, 5S, jidoka and TPM	IoT, CPS, Cloud computing, big data, robotics, AR, simulation, and additive manufacturing	Literature review	The connection between Industry 4.0 and LM improved organizational performance

2.4. Hypothesis Development

2.4.1. The Relationship between Industry 4.0 on Lean Manufacturing

Existing research suggests that Industry 4.0 supports LM [21,24,28]. This is because the digitalization of LM tools is enabled by Industry 4.0 [33]. Other researchers have shown the direct impact of Industry 4.0 technologies on LM tools [27,74]. For example, Ciano, Dallasega [74] developed a framework that showed direct relationships between Industry 4.0 technologies and LM tools. On the other hand, Rosin, Forget [27] explained the connection between Industry 4.0 technologies and LM principles. Sony [84] revealed that standardized processes, material and information flow, and waste reduction enable effective Industry 4.0 implementation. Chiarini, Belvedere [33] highlighted that Industry 4.0 technologies enhance leanness. For example, the use of smart sensors improves TPM, and a reduction of Work In Progress (WIP) can be achieved through the use of Radio-Frequency Identification (RFID) [33]. Pereira and Sachidananda [75] also highlighted that Industry 4.0 significantly and positively affected LM by offering focused and precise information to employees to find and mitigate waste. Value Stream Mapping (VSM) also benefits from Industry 4.0 technologies that allow automatic data collection of waste and other non-value-added activities in real-time [85] and value stream maps to be generated automatically [81]. It is therefore hypothesized that:

H₁. *Industry 4.0 technologies positively impact LM.*

2.4.2. The Relationship between Industry 4.0 and Sustainable Performance

Industry 4.0 is projected to take a significant role in guiding manufacturing organizations toward long-term sustainability. Industry 4.0 makes it easier to achieve greater process integration and enhance organizational performance across economic, social, and environmental sustainability [4]. Economically, Industry 4.0 significantly impacts production flexibility, product customization, and value generation, contributing to higher customer satisfaction [86,87]. Furthermore, Industry 4.0's digitalization and automation features propel manufacturing companies toward higher quality, shorter lead times, and

lower manufacturing costs. Environmentally, Industry 4.0 technologies enable businesses to implement data-driven techniques for gathering information throughout the product life cycle, from process parameters to material attributes [88], thus assisting companies in efficiently allocating raw materials, water, and energy. Socially, Industry 4.0 provides numerous opportunities for workers to master emerging technologies, boosting their motivation, job satisfaction, and drive. Furthermore, new technologies improve safe working conditions. Thus, it is hypothesized that:

H₂. *Industry 4.0 has a direct relationship with sustainable performance.*

2.4.3. The Relationship between LM and Sustainable Performance

LM principles have been crucial for any firm to meet sustainability goals [89]. Environmentally, the LM philosophy enhances product quality and reduces the quantity of stored raw materials and work in progress resulting in lower pollution levels and resource depletion rates [76]. Furthermore, the VSM tool aids in charting raw materials, water, and energy usage, thus helping the conscientization of waste reduction and helping economic sustainability. In addition, LM brings positive environmental performance results through TPM and JIT to lower pollution, resource use, and energy consumption [90]. Thus, it is hypothesized that:

H₃. *LM has a direct and positive impact on sustainable performance.*

2.4.4. The Moderating Effect of Lean Duration on the Association between Industry 4.0 and LM

The literature on operations management reveals that Lean implementation results are challenging to sustain. This is because organizations must change their culture and adjust to new procedures and techniques of doing work [91]. Therefore, companies that continue to witness Lean success have employees who continuously seek improvement in their workplaces. On the other hand, it is challenging to develop an LM environment quickly because significant time is needed for the management and employees to adapt to the philosophy [92]. Time has been highlighted as a critical component influencing the successful transmission of principles, tools, and employee behavior when implementing Lean [93]. The literature search done by the authors revealed that the study has shown how Lean duration impacts the adoption of Industry 4.0. Therefore, it is hypothesized that:

H₄. *Lean duration acts as a moderating variable on the relationship between Industry 4.0 and LM, such that the longer the adoption, the greater the implementation of Industry 4.0 (Figure 1).*

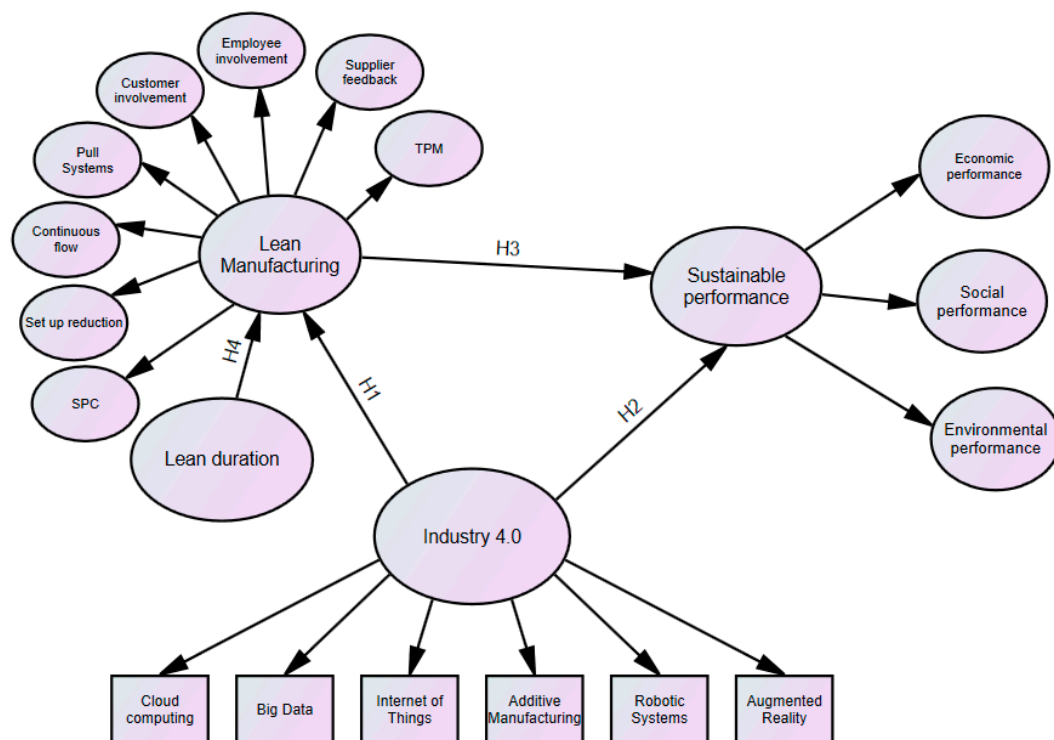


Figure 1. Research model.

3. Methodology

In conducting the study, three steps were followed: (i) developing a questionnaire, (ii) data collection, and (ii) data analysis.

3.1. Questionnaire Development

The study used a survey questionnaire (Appendix A) to assess the causal linkages between the factors and get generalizable judgments. The questionnaire's measuring items were taken from previous studies with good psychometric qualities. A five-point Likert scale was used to collect responses for the survey questions on Industry 4.0, LM, and sustainable performance, with (1) strongly disagree, (2) Disagree, (3) Undecided, (4) Agree, and (5) strongly agree. The survey items for LM were developed using Sanders, Elangeswaran [47], Shah and Ward [48], and [22]. In addition, the survey questions for Industry 4.0 were created using measuring items from Kamble, Gunasekaran [4], while the questions for sustainable performance were developed using Sajan, Shalij [55], and Kamble, Gunasekaran [4].

The survey was performed in three steps to ensure that the metrics were reliable and valid. Initially, the survey questionnaire was examined by six professionals from academia and industry for vagueness, readability, and appropriateness of measurements, following DeVellis and Thorpe [94] criteria. Two experts came from the industry, while four were from academia. Secondly, pilot research was done on 27 industry participants doing an LM professional certificate at the University of Kentucky to ensure validity and reliability. Only participants with previous manufacturing knowledge and expertise in the LM philosophy and Industry 4.0 could participate in the survey. Third, Cronbach alpha (α) values were calculated, and survey questions with scores below 0.70 were adjusted and reframed because they indicated vagueness, clarity, and suitability issues.

3.2. Data Collection

Initially, 517 manufacturing organizations in the USA representing various industries and firm sizes made up the sample. The researchers emailed a survey link to 355 manufacturing organizations throughout the USA. Additionally, 162 questionnaires were physically handed to participants who attended the LM professional certification. In order to get a sample that is representative of the population as a whole, manufacturing organizations were chosen at random from each state. Participation in the research study was kept voluntary, and the researchers sent follow-up messages after four weeks and eight weeks to remind the participants to answer and respond to the questionnaire. The cover letter attached to the email requested that the recipients only fill out the responses to the survey if they were familiar with Industry 4.0 and the LM philosophy.

The structure of the online survey questionnaire was such that respondents were required to provide answers to all the research questions. If respondents did not give all their responses, they were not permitted to complete the survey and send it in. The problem of incomplete questionnaires and missing data was resolved due to this restraint, and as a result, all online questionnaires were acceptable for the assessment. A total of 131 questionnaires were answered; however, five returned survey responses were excluded from the data sample because they had missing answers to numerous questions. The final sample had 126 responses representing a response rate of 24.37%. Table 4 gives the demographics of the respondents.

Table 4. Respondent demographics.

		Sample %
Industrial Sector	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
Respondent's profile	Industrial Engineer	7.14
	Manufacturing Manager	7.14
	Supervisor	3.57
	Operations Manager	8.93
	Executive	3.57
	Continuous Improvement Manager	12.50
	Lean Leader	12.50
	Process Manager	7.14
	Engineering Manager	5.36
	Senior Production Manager	14.29
	Quality Engineer	5.36
	Plant Manager	7.14
	Senior Director	5.36

Table 4. *Cont.*

		Sample %
Number of years in the organization	Less than 5 years	19.47
	Between 5 years—less than 10 years	27.43
	Between 10 years—less than 20 years	32.74
	More than 20 years	20.36
Size of the organization	Small Enterprises	3.64
	Medium-sized Enterprises	10.00
	Large Enterprises	86.36
Duration of Lean implementation	Between 1 year—less than 10 years	50.91
	Between 10 years—less than 20 years	29.09
	Between 20 years—less than 30 years	20.00

3.3. Data Analysis Techniques

Kolmogorov-Smirnov, for the two independent sample tests, were conducted on the data received from the respondents to factor in the non-response bias caused by the early and late responses. Harman's score on a single criterion was utilized to determine the existence of common method bias. The Structural Equation Modeling (SEM) model was used to assess the association between Industry 4.0 technologies, Lean Manufacturing, Lean duration, and sustainable performance. The authors used IBM SPSS version 28 to assess the outer model parameters such as Cronbach alpha, Average Variance Extracted (AVE), and composite reliability. Additionally, the maximum likelihood estimation method was employed to assess the validity of the outer model. The hypothesized inner model was validated with IBM AMOS version 28.

An assessment of model unidimensionality and the fit was done using parsimonious, incremental, and absolute model fit. The absolute fit examined how well the model fitted the data from the respondents. The parsimonious fit measures analyzed the model parsimony adjusted for the model complexity. The incremental fit measures the target versus the baseline model. The authors determined the following metrics: Chi-square value, root mean square error of approximation, degrees of freedom (df), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Non-Normed Fit Index (NNFI), Parsimony normed fit index (PNFI), Standardized root mean square residual (RMR), Akaike's Information Criteria (AIC), Bayesian Information Criterion (BIC) and Root Mean Square Error of Approximation (RMSEA).

4. Results

4.1. Measurement Model Assessment

The three first-order (LM, Industry 4.0, and sustainable performance) constructs were first measured with 57 questions. The number of questions was reduced using exploratory factor analysis, and 46 were used in the final analysis. Discriminant and convergent validity were two factors considered for evaluating the construct validity [28]. The principal component analysis examined the constructs' unidimensionality to determine convergent validity [95]. Bartlett's test of sphericity produced *p*-values less than 0.001 for every factor, and the Kaiser-Meyer-Olkin measure of sample adequacy exceeded the target threshold of 0.5. The items for the independent variables were loaded on a single construct and had eigenvalues greater than 1.0, which accounted for more than 50% of the variance. Furthermore, it had factor loadings over 0.5, all of which supported unidimensionality.

Average Variance Extracted (AVE) and Composite reliability were computed as further measures of convergent validity. AVE values greater than 0.5 and composite reliability > 0.7 are the suggested levels for acceptable convergent validity [96]. The authors adhered to Fornell and Larcker's suggestions to evaluate discriminant validity. The factor's AVE

values were higher than the square of its bivariate correlations with the other factors, which guaranteed discriminant validity. This condition was met in each instance. Cronbach's alpha coefficient was determined as a reliability test. Cronbach's alpha coefficient was determined as reliability analysis. All the summed scores had values greater than the suggested cutoff of 0.7 [97], making them trustworthy for further research.

The authors assessed the responses to five randomly selected survey questions for the early and late survey participants to investigate potential non-response bias. With a significance level of 0.05, the χ^2 tests for all five questions revealed no statistically significant variation between the early and late responders. This showed that non-response bias was not present [98]. Harman's single-factor test was used to analyze the data and look for common method bias. In addition, exploratory factor analysis was done by loading all the exogenous and endogenous variables. The test produced twelve factors with eigenvalues above 1 and a first factor explaining 22.22% of the variance. Therefore, it was believed that this study's common method bias posed no risk.

4.2. Structural Model Assessment

Eleven first-order constructs of each of the fourteen latent factors and forty-six observable variables were included in the comprehensive structural model created for this study to examine the effect of Industry 4.0, LM, and sustainable performance. The observed variables represented the endogenous latent factors.

4.2.1. Direct Effects of Industry 4.0 on Lean Manufacturing and Sustainable Performance

In order to examine the direct effects of Industry 4.0 on LM (H_1) and sustainable performance (H_2), SEM analysis was utilized. The result for the endogenous variables LM and the sustainable performance had R^2 values of 0.53 and 0.46, respectively. In addition, hypothesis H_1 , which stated that Industry 4.0 positively affects LM, was determined to be valid and significant ($\beta = 0.73$, $p = 0.001$). Additionally, hypothesis H_3 , which stated that LM has a positive relationship with sustainable performance, was also positive and significant ($\beta = 0.82$, $p = 0.001$). However, Industry 4.0 had a negative impact on sustainable performance (H_2) and was not supported ($\beta = -0.22$, $p = 0.251$).

4.2.2. The Indirect Effects of Industry 4.0 on Sustainable Performance through the Mediating Effect of Lean Manufacturing

Industry 4.0 positively impacted LM ($\beta = 0.73$, $p = 0.0001$), according to the outcomes of the structural model, and negatively impacted sustainable performance ($\beta = -0.22$, $p = 0.251$), as shown in Figure 2. The R^2 values for LM and sustainable performance were 0.53 and 0.46, respectively, and both had substantial overall R^2 values. Thus, the indirect effect of Industry 4.0 on sustainable performance was 0.958. Thus, the model results showed that full mediation occurred because the direct relationship between Industry 4.0 and sustainable performance was not substantial, while the indirect effect of Industry 4.0 on sustainable performance through the mediating effect of LM was positive and substantial.

4.2.3. The Moderating Effect of Lean Duration on the Relationship between Lean Manufacturing and Sustainable Performance

The moderating effects of Lean duration on the relationship between Industry 4.0 and LM were examined using SEM analysis. The Lean duration was calculated based on the overall number of years that LM had been adopted by the manufacturing organization and was given as a continuous variable. The regression weight for the interaction term (Lean duration $\times$ Industry 4.0) was positive and significant ($\beta = 0.321$, $p = 0.0001$). This showed that the presence of the moderator (Lean duration) strengthened the relationship between Industry 4.0 and LM. Furthermore, the moderator had a positive and significant relationship with LM. The moderation summary is given in Table 5.

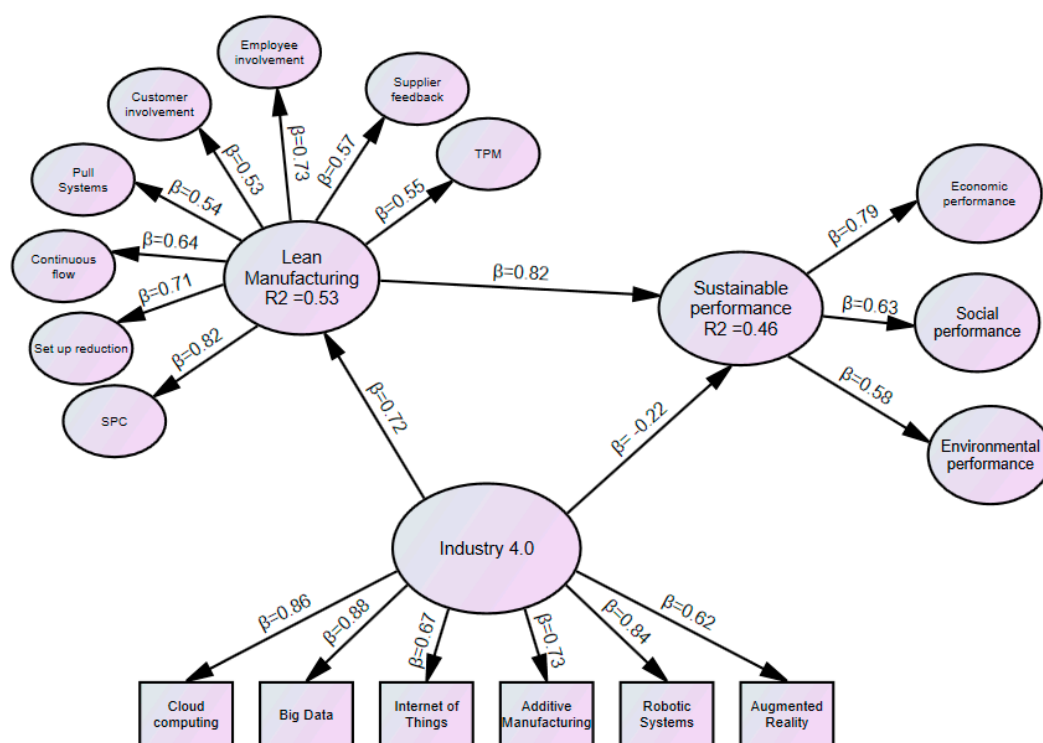


Figure 2. Full structural model.

Table 5. Regression Weights, *p*-values, and *t*-values.

			Estimate	SE.	CR.	<i>p</i>	Label
Lean Manufacturing	<—	Industry 4.0	0.610	0.117	50.329	***	
Lean Manufacturing	<—	Interaction Industry4.0 × Lean duration	0.321	0.008	30.359	***	
Lean Manufacturing	<—	Lean duration	0.242	0.006	20.623	***	
Sustainable Performance	<—	Lean Manufacturing	0.535	0.108	40.957	***	
Sustainable Performance	<—	Industry 4.0	−0.024	0.057	−0.428	0.669	

*** Indicates significance at $p < 0.001$.

4.3. Results and Analysis of the Two Models

Table 6 gives the fit indices such as NNFI, CFI, RMSEA, RMR, PNFI, AIC, and the χ^2/df statistic investigated for the two models 1 and 2. Model 1 reports the direct effect of Industry 4.0 on sustainable performance and the indirect impact of Industry 4.0 on sustainable performance through the mediating effect of LM. In order to test for the moderation effect, Model 2 included an interaction term between Industry 4.0 and Lean duration. The values of the two models for NNFI and CFI values were greater than 0.90, and the RMSEA values were lower than 0.08 [99,100]. Based on 5000 bootstrapped samples, the size and significance of indirect effects were evaluated using bias-corrected 95% confidence intervals (CI). The results revealed that model 2 ($\chi^2/df = 1.951$, CFI = 0.912, NNFI = 0.987 and RMSEA = 0.067, RMR = 0.062, AIC = 1538.487) provided a better fit to the data when compared to model 1 ($\chi^2/df = 1.825$, CFI = 0.928, NNFI = 0.918 and RMSEA = 0.066, RMR = 0.073, AIC = 1802.437). These results supported H_4 because it demonstrated that the Lean duration strengthens the relationship between Industry 4.0 and LM.

The connection between Industry 4.0 and Lean duration on LM is shown in Figure 3. To perform the basic effects test for the slopes of the lines, the researchers followed the recommendations of [101]. The findings showed that Lean duration moderates the association between Industry 4.0 and LM practices. Figure 3 gives the moderating impact of Lean duration at high and low levels. The results of the interaction effects revealed that the graph for high Lean duration was much steeper than the graph for low Lean duration. This showed that the impact of Lean duration on LM is stronger as Lean duration increases.

Thus, as the Lean duration increases, the strength between Industry 4.0 and LM increases. On the other hand, as the Lean duration decreases, the strength of the relationship between Industry 4.0 and LM decreases.

Table 6. Results of model comparisons.

Measures of Fit	Statistic Measure	Model 1	Model 2	Acceptable Fit Values
Absolute	χ^2 -Test statistic (d.f.)	1498.437 (975)	1573 (975)	N/A
	RMSEA	0.066	0.067	≤ 0.08
	RMR	0.073	0.062	≤ 0.10
Incremental	NNFI	0.918	0.987	≥ 0.90
	CFI	0.928	0.912	≥ 0.90
Parsimonious	Normed χ^2 (χ^2 /d.f.)	1.825	1.951	≤ 0.30
	PNFI	0.72	0.81	≥ 0.70
	AIC	1802.437	1538.487	N/A
	BIC	1533.513	1519.825	N/A

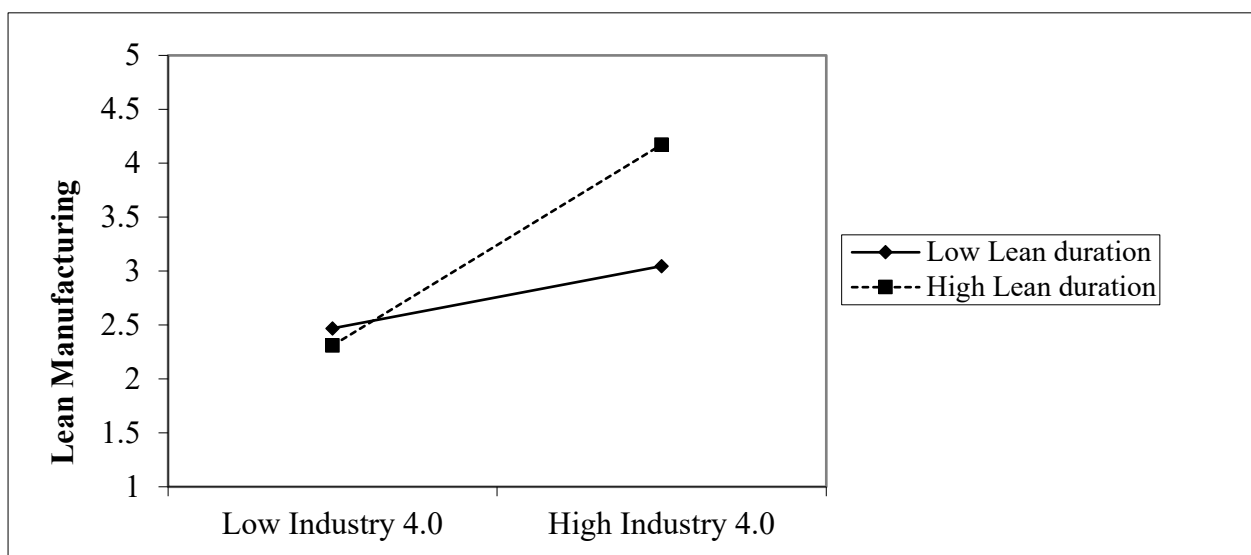


Figure 3. Moderating impact of Lean duration at high and low levels.

5. Discussion

The study evaluated the impact of Industry 4.0 on LM and sustainable performance. In addition, the authors analyzed the moderating effect of Lean duration on the association between Industry 4.0 and LM. The study results indicated that Industry 4.0 indirectly affects sustainable performance through the mediating effect of LM. Thus, the researchers discovered that the existence of LM as a mediator factor for the manufacturing industries in the USA increased the influence of Industry 4.0 on sustainable performance. The result also revealed that manufacturing organizations in the US could successfully enhance sustainable performance when LM is a vital component of the company's strategy.

LM focuses on growing and improving the human factor, which significantly affects and promotes organizational performance; therefore, implementing Industry 4.0 technology without this philosophy may not have an evident and immediate influence on sustainability performance. Additionally, the study findings showed that the combined effect of LM and industry 4.0 improves organizational sustainability, which was impossible by implementing either LM or Industry 4.0 alone. These results supported other studies showing the indirect impact of Industry 4.0 [76].

The study's findings also reveal that Industry 4.0 and LM technology will likely work together to cut waste and costs in the manufacturing sectors in the USA when it is not practical to employ either strategy alone. Although LM practices have previously demonstrated their effectiveness in several industries, it appears that LM can no longer cope with the shifting competitive forces and market dynamics [14]. For example, the phenomenon of capacity leveling is no longer consistent with significant market demand variations. In addition, LM practices are of constrained adaptability when it relates to shorter product life cycles and custom-tailored products, as evidenced by the lack of changeability in production systems, adaptability, and the labor-intensive modifications that are needed for varying manufacturing processes, buffer stocks, and cycle times [102].

The use of Industry 4.0 techniques such as CPS enables the tracking of production operations and output in real-time, which helps organizations to improve order processing and get more precise demand forecasts [103–105]. Cloud computing, intelligent bins, and RFID tags help lot tracking [106,107], while QR codes, Virtual Reality, RFID tags, and Augmented Reality assist inventory control and pull system adoption [13,78,108]. Using cloud computing, sensors, and real-time data sharing helps identify machine failure, quality control, and resource sharing [78,79]. Additionally, the Big Data technique is used in quality control, long-term planning, and VSM [108], while, Virtual Reality and Augmented Reality have made employee training easier [109]. However, the direct effect of Industry 4.0 on sustainable performance was not substantial. This revealed that implementing Industry 4.0 may not positively impact sustainable performance in the manufacturing industries in the USA. This result contradicts the findings of [4,76].

Our findings suggest that the relationship between Industry 4.0 and LM is stronger for organizations that have adopted the LM philosophy over a long time than those that have adopted LM over a short time. Thus, the research revealed that the length of time that LM has been in operation affects how well Industry 4.0 methods affect LM, which in turn affects sustainable performance. As a result, our empirical findings concur with those of [30,94,110], who have argued that implementing LM can only occur over time. Therefore, based on the results, the authors conclude that a company could eventually construct an LM system that produced maximum performance through continuous improvement if it fully utilized the Industry 4.0 technologies. This suggests that industry practitioners that persistently sustain LM may benefit more than followers in the long run. Since our thorough review of the literature indicated the challenge of discovering experiences as a result of the introduction of LM and Industry 4.0 in developing nations, we identify this as one of the distinctive contributions of our study.

5.1. Implications of the Study

5.1.1. Theoretical Implications

The study theoretically advances the body of research by empirically examining the moderating role of Lean duration in the connection between Industry 4.0, LM, and sustainable performance. The prior literature had highlighted the impact of Industry 4.0 on sustainable performance and LM, but it had not specifically addressed the moderating effect of Lean duration. In our research, Lean duration was discovered to be a critical moderating variable that expanded our understanding of the connection between Industry 4.0, LM, and sustainable performance and added to the body of knowledge on the sustainable operational performance of manufacturing organizations.

5.1.2. Practical Implications

The study's conclusions significantly impact consultants and industry professionals working on Industry 4.0 and LM initiatives in manufacturing organizations. For better sustainable performance, practitioners should also consider the effects of Lean duration adopting and managing Industry 4.0. Although the results show that Industry 4.0 has no direct, beneficial impact on sustainable performance, there is a positive impact on sustainable performance when LM acts as a mediating variable. This suggests that if

Industry 4.0 is built as a standalone application without LM, it might not contribute to sustainable performance. However, Lean duration is needed to overcome the constraints of Industry 4.0 deployment. As a result, it may be a significant facilitator for achieving sustainable performance.

6. Conclusions

Due to rising demand by governmental and non-governmental organizations for reducing pollution and raw materials usage, sustainable approaches such as LM and Industry 4.0 are crucial for manufacturing companies. The industrial sector can reach the desired economic and social progress by choosing the most sustainable idea without adversely affecting environmental factors. The main goal of this study was to investigate the impact of Industry 4.0 on LM and sustainable performance, as well as the moderating role of Lean duration in the relationship between Industry 4.0 and LM. This study empirically validated the association between Lean duration, Industry 4.0, LM, and sustainable performance in US Manufacturing organizations. The findings reveal that Lean duration moderates the association between Industry 4.0 and LM, and Industry 4.0 indirectly affects sustainable performance through the mediating effect of LM. Furthermore, these results showed that a Lean Manufacturing system could incorporate Industry 4.0 as long as it upholds lean principles and benefits the operation.

Limitations of the Study

The limitation of this research is that Industry 4.0 is described as a group of many technologies, including cloud computing, Big data, Virtual Reality, Big Data Analytics, Robotic Systems, IoT, and Additive Manufacturing. These technologies have various uses within a production system; thus, a business might choose to use only a few of them. The current research has not taken this into account. The present study does not explore the potential for incorporating these technologies in different industries. In order to explore the impact of LM on sustainable performance, it is advised that future research focus on one technology at a time and investigate how it influences LM. The sample responders for the current study were from diverse manufacturing industries in the USA, requiring and adopting different Industry 4.0 technologies and strategic decisions. Thus, additional research on specific industries may be conducted to develop a more comprehensive understanding of the connection between Lean duration, Industry 4.0, LM, and sustainable performance.

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Appendix A. Questionnaire

Table A1. Respondent demographics.

Number of years in the organization	Less than 5 years ☐	Between 5 and 10 years ☐	Between 10 and 20 years ☐	More than 20 years ☐
Number of employees in the organization	0–50 employees ☐	51–250 employees ☐	251–999 employees ☐	Over 1000 employees ☐

Table A1. *Cont.*

Type of industry i.e., electronics, motor assembly
Role within the organization
Number of years the organization has been in business
Number of years that the company has implemented Lean Manufacturing

Impact of Industry 4.0, Lean Manufacturing on Sustainable Operational Performance.

Table A2. Indicate by ticking the level of agreement or disagreement with the statement given that describes the level of adoption of Industry 4.0, Lean manufacturing practices based upon your company's current status.

Construct and Code	Item	Strongly Disagree 1	Disagree 2	Undecided 3	Agree 4	Strongly Agree 5
Supplier factors	Supplier Feedback 1. Our organization maintains constant communication with our major suppliers.					
	2. Our key suppliers receive feedback on delivery performance and quality from our organization.					
	3. Our organization strives to establish long-term relationships with our major suppliers.					
	Customer Involvement 1. Our company maintains strong communication with its clients.					
	2. Customers comment on the quality and timeliness of our service.					
	3. Customers are directly involved in existing product improvement and our company's new product development process.					
	4. Our customers are actively involved in product development and new product development.					
	5. Our customers communicate directly about the present and future demands with us.					
Process Factors	Pull Systems 1. The shipment of final goods pulls our production.					
	2. The demand for the next workstation pulls production at our workstation					
	3. Our organization uses pull production					
	4. Our organization utilizes signal containers or the Kanban system for production					
	Continuous Flow 1. Products that require similar processing procedures are categorized together.					
	2. Products that require similar routing methods are categorized together.					

Table A2. Cont.

Construct and Code	Item	Strongly Disagree 1	Disagree 2	Undecided 3	Agree 4	Strongly Agree 5
	3. The equipment is organized to maintain a constant flow of product families.					
	4. The factory layout is based on product families.					
	Set-up Time Reduction 1. Our workers use various approaches for reducing setup time.					
	2. Our company is constantly working to reduce setup time.					
	3. Our company's equipment offers a short setup time.					
Control and Human Factors	Statistical Process Control (SPC) 1. SPC covers the majority of the equipment/processes.					
	2. To control the process variance, we employ statistical approaches.					
	3. We use and display defect rate charts on the shop floor.					
	4. To uncover quality flaws, we employ cause-and-effect diagrams.					
	5. Any new product launch must start with a process capability study.					
	Employee Involvement 1. Our shop floor personnel feel and know that they play an essential part in problem-solving teams.					
	2. Our employees drive our company's suggestion scheme program.					
	3. Our shop floor staff are in charge of product/process improvement.					
	4. Our shop floor staff receive cross-functional training.					
	Total Productive Maintenance (TPM) 1. We devote a considerable percentage of our time to planned equipment maintenance activities daily.					
	2. All of our equipment is maintained regularly by our company.					
	3. All of the equipment at our organization has thorough and up-to-date maintenance records.					
Industry 4.0	1. We have adopted, or we are in the process of adopting computing services—including servers, storage, databases, networking, software, analytics, and intelligence.					
	2. We collect large volumes of data for use in analyzing our processes					
	3. We have adopted or we are in the process of adopting Internet of Things.					

Table A2. Cont.

Construct and Code	Item	Strongly Disagree 1	Disagree 2	Undecided 3	Agree 4	Strongly Agree 5
	4. We have adopted or we are in the process of adopting Additive Manufacturing/3D printing.					
	5. We have adopted or we are in the process of adopting Robotic Systems.					
	6. We have adopted or we are in the process of adopting the use of Virtual Reality whereby workers can be trained in a virtual environment.					
Sustainable Organization Performance	Economic Sustainability					
	1. Production costs are lower					
	2. Profits have increased					
	3. Product development costs are lower.					
	4. Energy costs are low					
	5. Inventory costs are low					
	6. Rework and rejection costs are low					
	7. Raw material purchasing costs have decreased					
	8. Waste treatment costs have decreased					
	Social sustainability					
	1. Working conditions have improved					
	2. Workplace safety has improved					
	3. Employee health has improved					
	4. Labor relations have improved					
	5. Worker morale has improved					
	6. Work pressure has decreased					
	Environmental Sustainability					
	1. Solid waste has reduced					
	2. Liquid waste has decreased					
	3. Gas emissions have reduced					
	4. Energy waste has been reduced					
	5. Hazardous and toxic materials have reduced					
	6. Environmental situation has improved					

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