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Lean Production Practices and Industry 4.0 Technologies Integration in Mexican Manufacturing Industry

Verónica Gabriela Valdivia-Plaza[1], Vianney Judith Robledo-Herrera[1] and Gonzalo Maldonado-Guzmán[1]

Abstract

Recently, there has been increased interest in the scientific, academic, and business communities regarding the relationship between lean production practices and Industry 4.0 technologies. However, most studies published in the literature have analyzed each of these concepts separately. Those that have analyzed lean production practices and Industry 4.0 technologies together have not only allowed manufacturing companies to improve the efficiency of their production processes but also their business performance. Despite this evidence, other studies published in the literature are highly critical of the knowledge and evidence provided regarding the integration of both concepts. Therefore, the relationship between lean production practices and Industry 4.0 technologies can be considered inconclusive. Therefore, this empirical study, using a sample of 410 manufacturing companies in Mexico, aims to identify the relationship between the adoption of lean production practices and Industry 4.0 technologies. The results obtained show that the adoption of lean production practices favors the adoption of Industry 4.0 technologies by manufacturing companies.

JEL classification numbers: O320.
Keywords: Lean production practices, Industry 4.0 technologies, manufacturing industry.

[1] Universidad Autónoma de Aguascalientes, Centro de Ciencias Económics y Administrativas, Departamento de Mercadotecnia, México.

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1. Introduction

In the last decade, there has been increasing interest among the scientific, academic, and business community in the relationship between lean production (LPP) practices and Industry 4.0 technologies (I4.0T) (Cannas *et al.,* 2025), particularly, not only because LPP helps manufacturing companies to eliminate unnecessary activities and optimize those activities that generate value (Womack & Jones, 1996), but also because of the call made in the literature to analyze the manufacturing industry from a human-centered perspective (Eriksson *et al.,* 2024), which will allow a better understanding of the complex systems in which humans and technology combine in a digital transformation (Nahavandi, 2019; Lu *et al.,* 2022; Eriksson *et al.,* 2022).

Previous research shows that the production and operations management literature lacks studies on the interaction between production practices, productivity, and I4.0T digital technologies (Masiko *et al.,* 2022). Therefore, the literature has called for manufacturing companies to develop more sustainable and efficient digital processes (Gatell & Avella, 2024) through the incorporation of LPP and I4.0T strategies (Skalli *et al.,* 2022). Furthermore, LPP and I4.0T have historically been perceived as distinct approaches and widely analyzed separately (e.g. Morseletto, 2020; Hughes *et al.,* 2022; Saporiti *et al.,* 2023), and only a few recent studies have explored the relationship between the two concepts (e.g. Yadav *et al.,* 2020; Ciliberto *et al.,* 2021; Pozzi *et al.,* 2023; Gatell & Avella, 2024; Cannas *et al.,* 2025). However, the relationship between LPP and I4.0T is not entirely clear and still generates many doubts in the literature (Eriksson *et al.,* 2024). Therefore, future studies need to focus on providing robust empirical evidence on the connection between both concepts (Tortorella *et al.,* 2019; Cifone *et al.,* 2021; Carlsson *et al.,* 2022; Eriksson *et al.,* 2022). Furthermore, the literature has recognized that LPP alone pose serious difficulties for the transformation and implementation of production systems, for example, by emphasizing changes in organizational culture and adaptive leadership (Maware & Parsley, 2022), and the importance of management commitment (Emiliani, 2018; Alieva & Powell, 2022). However, it has been shown in the same literature that the implementation of LPPs with an iterative and continuous improvement approach can significantly improve I4.0T (Sarro, 2020; Rossini *et al.,* 2021).

In this context, it has been shown in the literature that even though LPP and I4.0T have intrinsically distinctive characteristics (Eriksson *et al.,* 2024), particularly because LPP focus on iterative continuous improvement and human involvement, while I4.0T is characterized by disruptive technologies and radical changes in production processes (Rossini *et al.,* 2021), the existence of a close link between LPP and I4.0T has been demonstrated (Cifone *et al.,* 2021; Rossini *et al.,* 2021). Therefore, the objective of this study is the analysis and discussion of the effects that LPP exert on I4.0T in manufacturing companies. To achieve this objective, an empirical investigation was carried out in manufacturing companies in Mexico, using a sample of 410 companies, estimating the research model through Partial

Least Squares Structural Equation Modeling (PLS-SEM), with the use of SmartPLS 4.10.9 software (Ringle *et al.,* 2024).

Additionally, this study contributes to filling the existing gap in the literature on the link between LPP and Industry 4.0T (Eriksson *et al.,* 2024; Cannas *et al.,* 2025) and to providing robust empirical evidence on the effects of LPP on Industry 4.0T in a developing country (Cannas *et al.,* 2025). For these reasons, the overall effect of LPP in digital technology of Industry 4.0 may still be considered inconclusive (Eriksson *et al.,* 2024). Therefore, to complement and expand the limited body of knowledge, this paper addresses the following research question: *What is the relationship between Lean production practices and Industry 4.0 digital technologies in manufacturing firms?*

2. Preliminary Notes

2.1 Lean Production Practices

Although the concept of LP was first used in the literature in 1988 by John Krafcik to explain the success of Japanese manufacturing methods (Krafcik, 1988), it was described as a production system that is essentially oriented towards the reduction of industrial waste, continuous improvement and product quality (Womack *et al.,* 1990). In the last two decades, the literature on operations and production management has been characterized by an interest, on the part of the scientific and academic community, in the concept of LPP (Ciano *et al.,* 2019). On the one hand, because LPP were designed to eliminate industrial waste, product delivery time, inventories and improve business performance (Kóvacs, 2020; Tortorella *et al.,* 2020; Sancha *et al.,* 2020) and, on the other hand, because they improve employee morale and satisfaction, communication and attitude in decision-making (Hopp, 2018; Ciano *et al.,* 2019).

All these benefits of LPP help manufacturing firms reduce costs and contribute to improving customer satisfaction (Kovács, 2020). However, today's markets are increasingly competitive and require manufacturing companies to rapidly improve their production processes. This poses a challenge for companies due to the rapid demand for highly customized products (Kolberg *et al.,* 2017; Buer *et al.,* 2018). Therefore, it is not surprising that the literature considers LPP a strategy that improves the efficiency of production processes and maintains their competitive position both in the market and in the manufacturing industry (Eriksson *et al.,* 2024). However, recent studies have shown that LPP cannot be efficient on their own, which is why the implementation of I4.0T is required (Cagnetti *et al.,* 2021), which is why this relationship needs to be further analyzed (Hines *et al.,* 2023).

2.2 Industry 4.0 Technologies

Several studies published in the current literature have shown that I4.0T significantly improves industrial performance, flexibility, productivity, product delivery times, reduced production costs, and improved product quality (Moeuf *et al.,* 2018). Furthermore, I4.0T is attractive to many manufacturing firms, essentially because these benefits can be translated into the promise of individual and personalized production at the same cost as mass production (Wang *et al.,* 2016). However, the implementation of I4.0T requires profound changes in manufacturing companies, since the application of digital technologies such as Internet of Things, advanced robotics, big data analytics, additive manufacturing, augmented reality, and artificial intelligence requires structural changes in organizations (Alcácer & Cruz-Machado, 2019; Qu *et al.,* 2019).

Additionally, the digital advancement of I4.0T encompasses various key methodologies and trends that contribute to greater efficiency in production processes, value creation, and competitiveness (Sousa-Zomer *et al.,* 2020; Matt *et al.,* 2023). Therefore, I4.0T disruptively impacts manufacturing companies towards the generation of smart production ecosystems (Alcácer & Cruz-Machado, 2019). In this sense, I4.0T can be merged with LPP to help manufacturing companies make their production processes more efficient and flexible (Sarro, 2020; Jiang *et al.,* 2021; Deshmukh *et al.,* 2022). Therefore, manufacturing firms can increase their level of efficiency if they integrate I4.0T and LPP into their production processes (Gallo *et al.,* 2021; Ghobakhloo *et al.,* 2022), essentially because the adoption and implementation of LPP can play a fundamental role in guiding the application of I4.0T (Rossini e*t al*., 2021).

2.3 Lean Production Practices and Industry 4.0 Technologies

In the last decade, the publication of research analyzing the interaction between LPP and I4.0T has increased, with most of these studies focusing on the interest and complexity of the interconnection and interaction of both concepts (Cannas *et al.,* 2025). Thus, from a general perspective, publications have provided theoretical and empirical evidence that LPP and I4.0T are two complementary approaches (Parente *et al.,* 2020; Ciliberto *et al.,* 2021; Skalli *et al.,* 2023). Therefore, in this interaction, LPP are generally considered a critical success factor for the adoption of I4.0T (Pozzi *et al.,* 2023), whose benefits could be significantly increased in manufacturing companies if used properly (Parente *et al.,* 2020), both economic and social and environmental (Liq *et al.,* 2023).

In this context, the literature establishes that LPP facilitate the implementation of I4.0T in manufacturing firms (Cannas *et al.,* 2025), since, on the one hand, statistical process control allows data analysis, while JIT (just in time) and the participation of suppliers promote horizontal and vertical integration, through shared platforms that facilitate the monitoring and traceability of materials in real time (Ciano *et al.,* 2021). On the other hand, I4.0T can help improve operational processes carried out through the use of LPP in manufacturing firms (Cannas *et al.,* 2021), since, for example, it is possible to take advantage of technologies such as Internet of Things, automated guide vehicles, and big data analytics to improve LPP techniques and leave aside classic LPP (Cifone *et al.,* 2021).

Likewise, artificial intelligence could be used to support standard work, and autonomous robots, particularly automated guide vehicles, could support JIT

(Cifone *et al.,* 2021). Furthermore, big data analytics, simulation, cloud computing, Internet of Things, and artificial intelligence have also been shown in the literature to substantially improve the plan-do-check-act improvement cycle (Pozzi *et al.,* 2022). Other studies such as those by Mayr *et al.* (2018), Rosin *et al.* (2020), and Goienetxea-Uriarte *et al.* (2020) further analyzed the influence of LPP on I4.0T and provide complex insights into the reciprocal impacts these two concepts have on each other, revealing the transformative potential of I4.0T in the field of LPP and, vice versa, generating better outcomes for manufacturing companies (Cannas *et al*., 2025).

Additionally, studies published in the literature highlight the existing challenges for researchers and academics when combining LPP with I4.0T from different perspectives (e.g. Hoellthaler *et al.,* 2018; Tortorella *et al.,* 2019; Rossini *et al.,* 2021; Dornelles *et al.,* 2022), since, for example, the exclusive adoption and implementation of digital tools in LPP without considering effective pull systems can result in production in manufacturing firms remaining a push system (Tortorella *et al.,* 2019). Therefore, it is essential that a combination of LPP and I4.0T be fully adopted and implemented, as this will allow manufacturing companies to make rapid and flexible changes in the flow of raw materials, mass customization of products and delivery of production in the shortest possible time (Tortorella *et al.,* 2019; Kamble *et al.,* 2020).

In this same sense, the literature also considers it challenging to apply a dual LPP and I4.0T production system in manufacturing firms (Eriksson *et al.,* 2024), essentially because LPP are based on continuous improvement, structure, and a set of rules, while the development of I4.0T evolves dynamically by adopting disruptive technologies (Hoellthaler *et al.,* 2018; Rossini *et al.,* 2021). Furthermore, another substantial challenge is the consideration of LPP as a human-centered production system, and this aspect is not widely accepted in the I4.0T literature, since it generally presents a strong technocratic approach (Cagliano *et al.,* 2019; Dornelles *et al.,* 2022). Therefore, the simultaneous adoption and implementation of LPP and I4.0T entails challenges for manufacturing companies, which have to avoid focusing only on the digitalization of I4.0T (Souza-Zomer *et al.,* 2020), or only on the application of LPP digitalization (Maware & Parsley, 2022).

In this context, recently published studies suggest that the crucial success factors for the adoption of LPP and I4.0T in manufacturing companies are the technological readiness of the organization, as well as a change in the organizational culture (e.g. Antony *et al.,* 2023a, b), together with a shared understanding of the main characteristics of production (Eriksson *et al.,* 2022; Eriksson *et al.,* 2024). In this sense, the importance of the human-centered perspective has been argued in the current literature, since the coexistence of an LPP system and I4.0T is characterized by the adoption and implementation of advanced I4.0T (Eriksson *et al.,* 2024). At the same time, LPP should be coordinated and the company's vision recognized (Deshmukh *et al.*, 2022; Antony *et al.*, 2023a), along with the need to expand human skills and competencies (Alieva & Powell, 2022; Carlsson *et al.,* 2022; Masiko *et al.,* 2022).

Finally, although the adoption and implementation of LPP and I4.0T in manufacturing firms requires the application of different technological tools in the context of operational processes, both concepts have the same objective of significantly improving productivity and business performance (Liq *et al.*, 2023). For example, while the adoption of JIT requires LPP, the combination of I4.0 digital technologies through sensors could help manufacturing companies identify the location and condition of the products required in the market in real time (Rosin et al., 2020). Thus, based on the information presented above, it is possible to propose the following hypothesis:

H1: The greater the application of lean production practices, the greater the results of Industry 4.0 technologies.

To validate the hypothesis established in this research, an empirical study was applied to manufacturing firms in Mexico, using the National Directory of Economic Units (DENUE), which had a registry as of January 30, 2023, of 32,541 manufacturing companies with 10 or more employees (INEGI, 2023). The selection of manufacturing companies was carried out through simple random sampling, with a maximum error of ±4% and a reliability level of 95%, obtaining a sample of 410 companies. The survey, administered from February to June 2023, was directed to firms' managers, who, in turn, identified the most suitable individuals to respond to the various survey sections. Given their pivotal role in decision-making, general managers, well-informed about the study, adeptly identified individuals with the requisite expertise to address the survey's diverse sets of questions (Kuo & Chang, 2021).

Additionally, a comprehensive literature review was conducted to identify measurement scales that best suited manufacturing firms, and the Gastaldi *et al.* (2022) scale was identified as the most appropriate for measuring I40T, who measured this concept through 5 items. To measure LPP, the scale proposed by Farías *et al.* (2019) was used, who considered that this concept could be measured through 6 items. All items on the three scales used in this study were measured using a 5-point Likert-type scale with 1 = Total disagreement to 5 = Total agreement as the limits. As a preliminary step to data analysis, a reliability analysis of the LPP and I4.0T measurement scales was carried out, using the four most recommended indicators in the PLS-SEM literature: Cronbach's Alpha, Dijkstra-Henseler rho, Composite Reliability Index (CRI), and Average Variance Extracted (AVE) (Hair *et al.,* 2019), while for the measurement of discriminant validity the two most relevant indicators in the PLS-SEM literature were used: the Fornell and Larcker Criterion and the Heterotrait-Monotrait (HTMT) ratio (Henseler, 2018).

The results obtained show that Cronbach's Alpha has values that oscillate in a range between 0.938 - 0.945, Dijkstra-Henseler rho has values between 0.939 - 0.946 and CRI has values between 0.938 - 0.945, which are higher than the value of 0.70 recommended in the literature, while the AVE has values that oscillate in a range between 0.715 - 0.776, which are higher than the value of 0.50 recommended in the literature (Hair *et al.,* 2019) (Table 1 PANEL A). Regarding discriminant validity, the results obtained indicate that the AVE values of both LPP (0.846) and I4.0T (0.881) are higher than their respective correlation (0.533) (Table 1 PANEL B: Fornell-Larcker Criterion), while the HTMT value (0.533) is lower than the value of 0.80 recommended in the literature (Henseler, 2018), which indicates the existence of discriminant validity of the measurement scales of the LPP and I4.0T concepts.

Table 1: Measurement Model. Reliability, Validity, and Discriminant Validity

<table>
<tr><th colspan="5">PANEL A. Reliability and Validity</th></tr>
<tr><td>Variables</td><td>Cronbach's Alpha</td><td>Dijkstra-Henseler rho</td><td>CRI</td><td>AVE</td></tr>
<tr><td>Industry 4.0 Technologies</td><td>0.945</td><td>0.946</td><td>0.945</td><td>0.776</td></tr>
<tr><td>Lean Production Practices</td><td>0.938</td><td>0.939</td><td>0.938</td><td>0.715</td></tr>
<tr><th colspan="3">PANEL B. Fornell-Larcker Criterion</th><th colspan="2">Heterotrait–Monotrait ratio (HTMT)</th></tr>
<tr><td>Variables</td><td>1</td><td>2</td><td>1</td><td>2</td></tr>
<tr><td>1. Industry 4.0 Technologies</td><td>0.881</td><td></td><td></td><td></td></tr>
<tr><td>2. Lean Production Practices</td><td>0.533</td><td>0.846</td><td>0.533</td><td></td></tr>
</table>

Note: PANEL B: Fornell-Larcker Criterion: Diagonal elements (bold) are the square root of the variance shared between the constructs and their measures (AVE). For discriminant validity, diagonal elements should be larger than off-diagonal elements.

3. Main Results

To answer the research hypothesis posed in this study, the use of the PLS-SEM statistical technique with the use of SmartPLS 4.0 software (Ringle *et al.,* 2024) was considered. PLS-SEM was used because this study, on the one hand, includes a research model with various indicators (Sarstedt *et al.,* 2016; Rigdon *et al.*, 2017), which are necessary in the operational definition of the emergent construct that mediates all its effects (Henseler *et al.,* 2015). On the other hand, because the indicators do not have a common error term, contrary to what happens with research models that have causal formative indicators (Hair *et al.,* 2021), which is why these types of indicators share the same results, even when they are not unidimensional and do not share the same conceptual unit (Henseler, 2017).

The results obtained from the application of the PLS-SEM statistical technique are presented in Table 2, and indicate that the estimated data have a good statistical fit by obtaining a value of the adjusted R^2 of the endogenous variable (I4.0T = 0.289) higher than the value of 0.10 recommended in the literature (Hair *et al.,* 2020), a value of the SRMR lower than the value of 0.08 and the value of HI99 (0.027; 0.043) recommended in the literature, values of the unweighted least squares discrepancy (dULS) and geodesic discrepancy (dG) lower than the values of HI99 (0.050–0.124; 0.161–0.267, respectively) recommended in the literature (Sarstedt *et al.,* 2019), and the size of the effects of the independent variable (f2) on the value of the R^2 of the independent variable (I4.0T), suggests medium variations (0.415) (Hair *et al.*, 2017).

Table 2: Structural Model

Path	Path (*t-value; p-value*)	95% Confidence Interval	f^2	Support
LPP→I4.0T (H1)	0.535 (10.159; 0.000)	[0.432 – 0.637]	0.415	Yes
Endogenous Variable	Adjusted R^2	Model Fit	Value	HI99
		SRMR	0.027	0.043
I4.0T	0.289	dULS	0.050	0.124
		dG	0.161	0.267

Note: I4.0T: Industry 4.0 Technologies; LPP: Lean Production Practices. One-tailed t-values and p-values in parentheses; bootstrapping 95% confidence intervals (based on n = 5,000 subsamples); SRMR: standardized root mean squared residual; dULS: unweighted least squares discrepancy; dG: geodesic discrepancy; HI99: bootstrapping-based 99% percentiles.

Additionally, Table 2 also indicates that the data estimated using PLS-SEM verify our argument that LPP have a significant positive effect on I4.0T ($\beta = 0.535$; p-value 0.000). This result provides robust empirical evidence in favor of hypothesis H1, demonstrating that the adoption and implementation of LPP favors the adoption and development of I4.0T in manufacturing companies. Furthermore, to determine the predictive power of the final research model presented in Table 2, which can be implemented in the other subjects in the population (manufacturing companies in Mexico), the predictive power of the final model was analyzed using PLSpredict, the results of which are presented in Table 3.

Table 3: PLS-SEM Q^2predict and prediction error (descriptives)

	Q^2predict	Mean	Median	Observed Min.	Observed Max.	Cramér-von Mises Test Statistics	Cramér-von Mises p-value
Industry 4.0 Technologies	0.243	0.000	0.028	-4.438	3.091	17.210	0.000

Table 3 shows that the Q^2predict value of the dependent variable is positive, while the mean value of the mean prediction error of the PLS-SEM is zero (Industry 4.0 Technologies Q2predict = 0.243; PLS-SEM prediction error = 0.000), which indicates that the final research model has a high predictive power, obtaining similar results in any of the manufacturing companies in Mexico to which this same model is applied.

4. Discussion

The findings in this study support our argument that the adoption and implementation of LPP have a significant positive effect on the adoption of I4.0T by manufacturing companies in Mexico. This result is similar to those found by Rosin *et al*. (2020), Parente *et al.* (2020), Ciliberto *et al. (*2021), and Skalli *et al.* (2023). The main reasons that could explain this result are, on the one hand, that the managers of manufacturing companies are willing to address the challenges posed by the adoption and implementation of LPP and the application of I4.0T, and move towards the coexistence or fusion of LPP and I4.0T in all of the organizations' processes, which implies not only new challenges for managers but also achieving better business results than their main competitors.

On the other hand, LPP and I4.0T can help manufacturing companies not only improve their economic and financial performance, but also improve the social and environmental performance of the localities where they are located, by improving the labor, health, and safety practices of all their employees, as well as the quality of life and the economic, social, and environmental well-being of society as a whole. However, the literature has shown that the adoption and implementation of LPP and I4.0T is by no means the only solution to the problems faced by companies in the manufacturing industry (Gallo *et al.,* 2021; Jiang *et al.,* 2021). On the contrary, it is one of the various strategies that companies can adopt. However, to have a greater probability of success, companies must make fundamental changes in their processes and organizational culture.

In this context, it could be argued that one of the key aspects of the combination of LPP and I4.0T recognized in the literature is to recognize the importance of human capital when wanting to transform manufacturing companies (Eriksson *et al.,* 2024), which is why it is recommended that organizations consider the human being (Marcon *et al.*, 2022), and incremental aspects (Eriksson *et al.,* 2022), when adopting and implementing LPP and new I4.0T. This aspect coincides with the arguments in the literature that a successful application of LPP enhances people's capabilities (Rother, 2010) and with the finding that the implementation of I4.0T requires a human-centered perspective to achieve better results, not only economic but also social and environmental (Nahavandi, 2019; Breque *et al.,* 2021).

5. Conclusions

The findings of this study generate several conclusions, among the most important of which are the following. First, although a high percentage of manufacturing firms in developing countries face serious challenges in adopting and implementing LPP and new digital technologies of I4.0, it is possible to conclude that the adoption of LPP facilitates the adoption of I4.0T and increases the possibility of organizations significantly improving their economic and financial performance. However, the adoption and implementation of LPP and I4.0T in manufacturing firms in developing countries is not easy, particularly due to the uncertainty in the business environment that characterizes these types of countries. Therefore, firms must make changes in both their organizational structure and their organizational culture. Secondly, it is undeniable that the economies of developing countries, such as Mexico, are characterized by a hostile business environment that severely limits the adoption and implementation of LPP and new digital technologies of the I4.0. Therefore, it is possible to conclude that the application of LPP and I4.0T should be a priority for business management, as well as for policymakers and public administration. This is particularly true because of the results obtained from this study, which provide robust empirical evidence of the importance of the coexistence of both LPP and new digital technologies of the I4.0. Simultaneous adoption and application can help manufacturing companies improve their economic, social, and environmental performance.

Finally, this empirical study has several limitations that must be considered before interpreting the results obtained. First, the study focused exclusively on manufacturing companies, so any comparison with other sectors is a limitation. Second, the study considered only manufacturing companies with 10 or more employees, ignoring those with fewer than 10 employees. Therefore, the results could be different if a sample of manufacturing companies with fewer than 10 employees were considered. A fourth and final limitation is that this study only performed a cross-sectional analysis with data obtained through a survey, ignoring the possible temporal effects of the LPP and the I4.0T. Therefore, longitudinal studies would be important to corroborate the results obtained.

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