

Technological digital transformation in the automotive and aerospace sectors: a lean 4.0, Industry 4.0, and logistics 4.0 perspective

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Abstract

Purpose – Digital Technologies of Industry 4.0 (DTI4.0) have revolutionized decision-making processes, while Lean 4.0 (L4.0) has evolved to support continuous improvement and enhance integration with Logistics 4.0 (LG4.0). Recent studies indicate that L4.0 represents a transformation of traditional lean practices, reconfigured to meet the demands of DTI4.0, enabling firms to address challenges related to speed, complexity, and operational efficiency. However, despite the growing interest in these paradigms, there remains a lack of comprehensive empirical research examining the interrelationships and combined effects of L4.0, DTI4.0, and LG4.0. This study investigates how L4.0 influences both DTI4.0 and LG4.0, with a particular focus on the automotive and aerospace industries.

Design/methodology/approach – A theoretical framework was developed and empirically tested using survey data from 378 Mexican manufacturing firms, analyzed through Partial Least Squares-Structural Equation Modeling (PLS-SEM).

Findings – The findings reveal that the simultaneous implementation of L4.0 and DTI4.0 significantly enhances LG4.0 activities. Furthermore, the results confirm that DTI4.0 plays a mediating role in the relationship between L4.0 and LG4.0, offering both theoretical insights and practical implications for firms navigating digital transformation in production and logistics.

Originality/value – The paper addresses an important gap by proposing a conceptual framework that enhances the comprehension of the intricate relationships between L4.0, DTI4.0, and LG4.0, with particular emphasis on their adoption and reciprocal effects. In addition, the paper provides strong empirical insights that contribute to resolving inconsistencies in the literature concerning the mediating function of Industry 4.0 in linking Lean 4.0 with Logistics 4.0.

Keywords Lean 4.0, Industry 4.0, Logistics 4.0, Automotive industry, Aerospace industry

Paper type Research article

1. Introduction

Over the past 2 decades, manufacturing companies have faced an increasingly volatile and competitive business environment, driven by substantial growth in market demand and rapid technological advancements (Lu and Xu, 2018; Lestari *et al.*, 2021). This dynamic landscape has compelled firms to adopt innovative strategies and technologies to sustain competitiveness (Hines and Netland, 2022). Among the most widely implemented approaches are Lean manufacturing and Industry 4.0 (I4.0). Recently, these paradigms have converged under the concept of Lean 4.0 (L4.0) or Lean Industry 4.0, which integrates lean principles with the digital technologies of Industry 4.0 (DTI4.0) (Rosin *et al.*, 2022; Arey *et al.*, 2021). Both L4.0 and DTI4.0 have emerged as critical frameworks enabling manufacturing firms to navigate the complexities of a globalized market (Kassem *et al.*, 2024).

Despite their common aim of enhancing organizational productivity (Hines and Netland, 2022), ambiguity persists within industry and academic circles regarding how these two



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concepts interact. This uncertainty is partly rooted in the historical association of Lean with low-tech, incremental improvements (Dickmann, 2008), contrasted with Industry 4.0's emphasis on advanced digital technologies, which some lean advocates view with scepticism (Pagliosa *et al.*, 2021). Consequently, the integration represented by Lean 4.0 has garnered growing interest from both scholars and practitioners seeking to understand how the fusion of these approaches can significantly improve financial and operational outcomes in manufacturing (Rossini *et al.*, 2019).

Moreover, the adoption of DTI4.0 within Lean activities (L4.0) and logistics processes (LG4.0) introduces increased complexity in management, production, and supply chain operations (Cimini *et al.*, 2020a). Many manufacturing companies worldwide remain in transitional phases, moving from traditional production and logistics toward innovative models incorporating DTI4.0, which promise enhanced efficiency and greater value creation (Cimini *et al.*, 2020b; Lagorio *et al.*, 2021). However, the literature acknowledges that realizing these benefits is a significant challenge (Yilmaz *et al.*, 2022), particularly because the combined implementation of L4.0, DTI4.0, and LG4.0 is complex and resource-intensive, especially in emerging economies (Qureshi *et al.*, 2023).

The growing interest in integrating Lean 4.0 and Digital Technologies of Industry 4.0 within Logistics 4.0 among academic, scientific, and industrial communities highlights the need for empirical validation of their combined benefits in reducing costs, improving efficiency, and creating value (Buer *et al.*, 2020; Tortorella *et al.*, 2021c). Despite this interest, the literature still lacks comprehensive, data-driven analyses clarifying the interrelationships between L4.0 and DTI4.0 (Kurpjuweit *et al.*, 2019; Calabrese *et al.*, 2020; Dora *et al.*, 2020). Similarly, although recent research has begun exploring the relationship between L4.0 and DTI4.0 (Bittencourt *et al.*, 2019), studies remain scarce (Bittencourt *et al.*, 2021; Mahdavishtarif *et al.*, 2022), with most focusing narrowly on manufacturing processes and overlooking critical areas such as logistics activities (Rosin *et al.*, 2020; Müller and Birkel, 2020; Taghavi and Beauregard, 2020). From a theoretical perspective, despite an increasing number of publications on DTI4.0 adoption in manufacturing (e.g. Buer *et al.*, 2018; Weking *et al.*, 2019; Culot *et al.*, 2020), limited research has addressed the intersection of L4.0, DTI4.0, and LG4.0 (Wagner *et al.*, 2017; Gillani *et al.*, 2020). To fill these research gaps and industrial needs, this study addresses the following research questions:

RQ1. What is the relationship among L4.0, I4.0, and LG4.0?

RQ2. What mediating role does I4.0 play in the relationship between L4.0 and LG4.0 within the automotive and aerospace sectors?

To investigate these questions, an empirical study was conducted involving 378 automotive and aerospace manufacturing firms in Mexico. A theoretical framework hypothesizing the relationships among L4.0, DTI4.0, and LG4.0 was developed and empirically tested using Partial Least Squares-Structural Equation Modeling (PLS-SEM) with SmartPLS 4.0 software (Ringle *et al.*, 2022). The Mexican automotive and aerospace industries are particularly relevant due to their high levels of automation (ProMéxico, 2018; Cebreros *et al.*, 2020) and their significant contributions to employment and GDP (INEGI, 2023).

Theoretically, this study makes two main contributions. First, it fills a critical gap by advancing a conceptual model that deepens understanding of the complex interplay among L4.0, DTI4.0, and LG4.0, focusing on their implementation and mutual influence. Second, it offers robust empirical evidence to reconcile conflicting findings in the literature regarding the mediating role of Industry 4.0 between Lean 4.0 and Logistics 4.0 (Cifone *et al.*, 2021; Yilmaz *et al.*, 2022). Practically, our findings provide manufacturing decision-makers, especially in the automotive and aerospace sectors, with actionable insights and a validated framework to guide the integrated adoption of Lean 4.0, Industry 4.0, and Logistics 4.0. This framework aids readiness assessment, strategy development, and risk mitigation during digital transformation, while also offering valuable lessons for emerging economies like Mexico.

2. Literature review

2.1 Lean 4.0 and logistics 4.0

Lean is not only a management concept that helps manufacturing companies become more competitive by eliminating industrial waste (Qureshi and Mewada, 2025), but it has also transformed manufacturing firms by introducing fundamental changes to managerial leadership styles, employees' daily operational practices, and particularly, logistics activities (Liq et al., 2023). However, the literature has shown that Lean alone is insufficient to address competitive pressures in the era of emerging digital technologies brought about by the Fourth Industrial Revolution (Miqueo et al., 2020; Rosin et al., 2020). As a result, the integration of digital technologies such as the Internet of Things (IoT), Augmented Reality, Cloud Computing, and Big Data Analytics has revolutionized traditional Lean practices, evolving them into Lean 4.0 (L4.0), and similarly transformed logistics operations into Logistics 4.0 (LG4.0) (Liq et al., 2023).

The combination of new digital technologies in the concepts of lean (L4.0) and logistics (LG4.0) helps manufacturing companies to increase their efficiency, on the one hand, through L4.0 to facilitate the application of the Just in Time system and the precision state of the machinery, which is defined as *"a perspective of lean that can implement the new digital technologies in its main tools to improve waste detection and reduction in both digital and processes"* (Gomes et al., 2022, p. 3) and, on the other hand, LG4.0 which is the transformation of logistics activities into smart logistics with the use of location, detection, networking, and data processing technologies (Frontoni et al., 2020), which is defined as *"a variety of characteristics, like real-time big data analytics, innovative manufacturing leading to reduce storage requirements, autonomous robots for optimized inventory control, and transformation from hardware-oriented logistics to software-oriented logistics"* (Strandhagen et al., 2017, p. 360).

Within this context, the implementation of L4.0 significantly boosts the efficiency of LG4.0, influencing the efficiency of the value chain, the well-being of logistics operators, and the overall organizations performance (Alfonso et al., 2021). Furthermore, L4.0 aids manufacturing firms in maximizing value and reducing waste through various diagnostic and process improvement techniques and tools (Arezes et al., 2015). When L4.0 is linked with LG4.0 practices a top priority for firms to eliminate waste and enhance overall organizational efficiency (Melo et al., 2020). However, the relationship of L4.0 in LG4.0 requires a constant effort to integrate existing technologies with new digital technologies to respond to the needs of manufacturing companies in the automotive and aerospace industries in very specific processes, and they must be flexible and easy to program (Waschull et al., 2020).

Kolberg and Zuhlke (2015) and De Felice et al. (2018) demonstrated that L4.0 can transform logistics activities into intelligent LG4.0, through the application of lean techniques such as automatic identification, location and detection technologies, networks, and data processing. Therefore, the literature considers the importance of integrating L4.0 into all business activities, particularly in manufacturing, inventory control, and logistics activities (Edirisuriya et al., 2018). Thus, LG4.0 plays a fundamental role in manufacturing firms, not only in the automotive and aerospace industries but in any industrial sector, primarily impacting product production, on-time delivery, and customer satisfaction (Edirisuriya et al., 2018). Consequently, the integration of L4.0 into all LG4.0 practices helps companies improve the efficiency of industrial activities (Kumar et al., 2017). Hence, considering the presented information, the following hypothesis is proposed.

H1. A greater application of Lean 4.0 leads to better outcomes in Logistics 4.0

2.2 Lean 4.0 and Digital Technology Industry 4.0

Recently, there has been growing interest within the scientific and academic communities in understanding how Lean 4.0 (L4.0) and Digital Technologies of Industry 4.0 (DTI4.0) interact

to enhance production performance (e.g. [Ejsmont et al., 2020](#); [Bittencourt et al., 2021](#)). However, most existing studies have taken the form of broad literature reviews (e.g. [Kipper et al., 2020](#); [Nuñez-Merino et al., 2020](#); [Pagliosa et al., 2021](#); [Elafri et al., 2022](#); [Stojanovic, 2022](#)), with only a few employing quantitative analyses using survey data from manufacturing firms (e.g. [Tortorella et al., 2019](#); [Buer et al., 2021](#)). As a result, several researchers have called for more robust empirical evidence to clarify the relationship between L4.0 and DTI4.0 (e.g. [Sanders et al., 2016](#); [Buer et al., 2018](#); [Rossini et al., 2019](#)), particularly because current evidence in the literature remains insufficient to confirm a strong linkage between these two paradigms ([Hines et al., 2023](#)).

Most published studies have identified a synergistic effect between L4.0 and DTI4.0 (e.g. [Ejsmont et al., 2020](#); [Rosin et al., 2021](#); [Buer et al., 2021](#)). For instance, [Ciano et al. \(2021, p. 1387\)](#) suggested that L4.0, “with its streamlined process orientation, clearly defined tasks and timings, standardized workflows and workspaces, and focus on virtual control and transparency,” facilitates the implementation of Industry 4.0 practices such as information sharing and automation. Accordingly, the literature shows that focusing solely on the adoption of L4.0 is not sufficient (e.g. [Salvadorinho and Teixeira, 2020](#); [Amrani and Vallespir, 2021](#)), nor is the isolated implementation of DTI4.0 (e.g. [Breque and De Nul, 2021](#); [Tortorella et al., 2023](#)), to achieve higher levels of efficiency and competitiveness. Instead, the simultaneous adoption and integration of both concepts is necessary ([Hines et al., 2023](#)).

Additionally, L4.0 facilitates the adoption of DTI4.0, particularly because the incorporation of digital technologies in L4.0 such as, for example, internet of things, cloud computing, data analytics, artificial intelligence, machine-to-machine communication, and cyber-physical systems, reduce the delivery time, labor, materials and resources and industrial waste as much as possible ([Qureshi et al., 2022a, b](#)). In this sense, more manufacturing firms are implementing L4.0 to improve DTI4.0 ([Qureshi et al., 2023](#)), especially, because both the L4.0 and the I4.0 have the common objective of boosting the productivity and flexibility of the production processes of manufacturing companies, as well as the elimination of waste in production processes ([Qureshi et al., 2023](#)).

Regardless of the perspective considered in the research, the significant interest from the scientific, academic, and business communities in the topic is evident. Nevertheless, the contributions in the literature still make it challenging to assess the impact of L4.0 on the DTI4.0 in manufacturing firms ([Cifone et al., 2021](#)). This is mainly because most of the studies in the literature have a theoretical focus (e.g. [Buer et al., 2018](#); [Shahin et al., 2020](#)), or are centered on exploring the potential impacts of L4.0 on the DTI4.0 (e.g. [Rossini et al., 2019](#); [Rosin et al., 2020](#); [Tortorella et al., 2021a, b](#)). However, despite the risks and barriers, the implementation of L4.0 in DTI4.0 generates considerable economic, social, and environmental benefits ([BMAS, 2017](#); [Tortorella and Fettermann, 2018](#)). Considering those arguments, the following hypothesis is proposed.

- H2. A greater application of Lean 4.0 leads to a greater application of Digital Technology Industry 4.0

2.3 Digital Technology Industry 4.0 as a moderating variable

Recent advances in information and communication technologies, combined with growing pressure for the digitalization and automation of production processes, have paved the way for significant improvements in logistics activities ([Strandhagen et al., 2017](#)). In this context, the rapid development of Industry 4.0 digital technologies (DTI4.0), defined as “a combination of different technologies such as additive manufacturing, simulation, robots and autonomous vehicles, augmented and virtual reality, IoT, cloud, and cybersecurity” ([Rüßmann et al., 2015, p. 56](#)), has led to the emergence of Logistics 4.0 (LG4.0). In the literature, LG4.0 is described as a system that enables the sustainable fulfillment of customer demand through the integration of digital technologies ([Winkelhaus and Grosse, 2020](#)) or as a new method, toolkit, and

paradigm that supports manufacturing firms in becoming more efficient and competitive (Szymanska *et al.*, 2017).

Moreover, DTI4.0 has reshaped the Logistics 4.0 paradigm through various applications and technologies that have enhanced supply chains and transportation services (Caliskan *et al.*, 2025). The integration of digital technologies, such as the Internet of Things, cloud computing, autonomous devices, and big data, plays a critical role in achieving a fully developed LG4.0 system (Caliskan *et al.*, 2020). These technologies not only enable manufacturing firms to improve logistics operations but also to respond to customer needs more quickly and flexibly. By embedding advanced digital solutions, manufacturers can achieve greater agility and responsiveness (Caliskan *et al.*, 2025). Therefore, the early adoption and implementation of DTI 4.0 is essential for the timely optimization of both production and logistics activities (Kucukaltan *et al.*, 2022).

In this sense, DTI4.0 facilitates the application of digital technologies in logistics activities, through greater visibility and transparency of companies in the supply chain, which generates not only economic benefits but also social ones, and environmental (Gupta *et al.*, 2021). Therefore, the relationship between DTI4.0 and LG4.0 guarantees the generation of a highly responsive and dynamic ecosystem that can respond to customer requirements and needs and, at the same time, achieve environmental objectives (Parhi *et al.*, 2022). In this context, recent studies have emphasized that, on the one hand, the adoption of DTI4.0 improves LG4.0 activities (e.g. Torbacki and Kijewska, 2019; Sun *et al.*, 2022; Parhi *et al.*, 2022) and, on the other hand, the need for future research to focus on the use of DTI4.0 to enhance the sustainable performance of logistics processes in manufacturing firms (e.g. Esmaeilian *et al.*, 2020; Sun *et al.*, 2022).

Additionally, the application of DTI4.0 in manufacturing firms in the automotive and aerospace industries has a positive influence on all LG4.0 processes. On one hand, from raw material acquisition to product delivery, helping manufacturing firms maintain high customer service standards and uphold their level of global competitiveness (Abdirad and Krishnan, 2021), and on the other hand, in the use of sensors in cyber-physical systems (e.g. accelerometers, GPS, cameras, humidity sensors) (Berger *et al.*, 2016), intelligent transportation systems usage (Kovalsky and Micieta, 2017), telematics technology usage (Kijewska *et al.*, 2016), support for blockchain technology (Abeyratne and Monfared, 2016), using electronic marketplace platforms (Wanga *et al.*, 2011), and augmented reality (Cirulis and Ginters, 2013). Thus, according to the evidence provided in the literature, the following hypothesis is proposed.

- H3. A higher application of Digital Technology Industry 4.0 leads to a higher application of Logistics 4.0

Digital technologies associated with Industry 4.0 (DTI4.0), such as sensors, manufacturing execution systems (MES), supervisory control systems, cloud computing, and big data analytics, can significantly enhance the connectivity and interaction between Lean 4.0 (L4.0) and Logistics 4.0 (LG4.0) activities (Tortorella *et al.*, 2019). This integration enables manufacturing firms to achieve more efficient and effective production processes and service delivery (Hermann *et al.*, 2016; Ganzarain and Errasti, 2016; Xu *et al.*, 2018). Improved interconnection and communication between work cells and stations can also facilitate a flexible, fast, and high-quality flow of materials and services (Erol *et al.*, 2016; Thoben *et al.*, 2017). In turn, this enhances visibility into continuous flow implementation in both production (L4.0) and logistics operations (LG4.0), which can undoubtedly improve manufacturing performance (Tortorella *et al.*, 2019).

However, the adoption and implementation of DTI4.0, such as the Internet of Things (IoT), cloud computing services, and additive manufacturing, within L4.0 and LG4.0 activities may sometimes yield only marginal gains in product and service innovation. This can lead to frustration among managers due to the high investments and expectations involved (Cheng *et al.*, 2018; Buer *et al.*, 2018). In this context, Tortorella *et al.* (2019) found that DTI4.0 can act

as a mediating variable, improving the relationship between lean production and operational performance. Similarly, [Liq et al. \(2023\)](#) suggested that DTI4.0 adoption can serve as a mediator between lean production and sustainable performance.

Additionally, in this line, manufacturing firms need to strategically plan their investments in infrastructure, technology, and staff training for the adoption and implementation of DTI4.0. The literature has consistently demonstrated that the integration of DTI4.0 enhances business performance, L4.0, and LG4.0 ([Qureshi et al., 2023](#)). As a result, it is assumed that L4.0 assists organizations in meeting both local and global demands through the application of DTI4.0, leading not only to sustainable manufacturing but also to improving LG4.0 activities ([Yadav et al., 2021](#)). Thus, the implementation of DTI4.0 in manufacturing firms is crucial for effective L4.0 application, as it positively influences outcomes in LG4.0 activities ([El Faydy and El Abbadi, 2023](#)), particularly as the relationship between L4.0 and LG4.0 strengthens with DTI4.0 ([Rahardjo et al., 2023](#)).

Additionally, the implementation of DTI4.0 through the use of various emerging digital technologies such as artificial intelligence, internet of things, big data, autonomous vehicles, and robotics significantly improves LG4.0 activities by reducing polluting gas emissions and improving the transportation planning of products ([Parhi et al., 2022](#)), hence transforming the entire supply chain ecosystem of the manufacturing firms ([Attaran, 2020; de Souza et al., 2022](#)). This is relevant because the adoption and application of DTI4.0 can further boost the efficiency of processes for companies already implementing L4.0, leading to improved logistics performance ([Rossini et al., 2021](#)). Accordingly, executives in manufacturing firms are tasked with refining this new strategy, organizational structure, and management skills to remain competitive in the current market ([Sartal et al., 2022](#)). Therefore, based on the previous evidence, the following research hypothesis can be formulated.

H4. Digital Technology Industry 4.0 serves as a mediating variable between Lean 4.0 and Logistics 4.0

[Figure 1](#) illustrates the theoretical research framework developed for this research based on the established hypotheses. The framework allows the understanding of the antecedents and consequences of L4.0 as described by the causal relationships between DTI4.0 and LG4.0.

3. Methodology

This study was conducted taking as a reference the business directory of the Mexican Association of the Automotive Industry (AMIA), which had a record of 950 companies as of January 30, 2023, and the business directory of the Mexican Federation of the Aerospace Industry (FEMIA), which had a record of 350 companies as of January 30, 2023. It is important to note that companies belonging to both AMIA and FEMIA are associated with various national and international chambers and business organizations, so the study did not focus on a particular group or business association. Likewise, this study was focused on manufacturing firms in the automotive and aerospace industries, particularly because they have not received extensive attention in the literature concerning how they are managing the adoption of digital

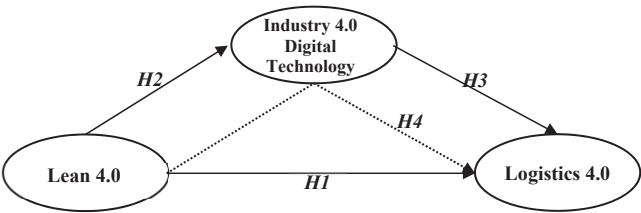


Figure 1. Theoretical research framework

technologies and how these are affecting the traditional lean and logistics practices that have been implemented for several decades (Tortorella *et al.*, 2016).

Manufacturing firms in the automotive and aerospace industries were selected through random sampling, with a margin of error of $\pm 4\%$ and a 95% significance level. This approach indicated that 320 responses were needed for the study to have statistical significance. The survey employed for data collection was distributed to 650 firms across both industry types in Mexico, resulting in 378 responses. This ensured the final sample accurately represented both sectors. 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 questionnaire 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 questionnaire's diverse sets of questions (Yu and Tsai, 2018; Kuo and Chang, 2021).

A literature review was conducted to identify the most suitable measurement scales for L4.0, DTI4.0, and LG4.0. For measuring L4.0, the scales by Ciano *et al.* (2021), Khin and Hung-Kee (2022), and Qureshi *et al.* (2022b) were adapted, resulting in 4 items to measure L4.0. To measure LG4.0, the scale by Dallasega *et al.* (2022), who measured it through 9 items, was employed. Finally, for measuring DTI4.0, 8 items developed by Feldmann *et al.* (2010), Akanmu and Anumba (2015), Zhou *et al.* (2015), Zhong *et al.* (2016), Tjahjono *et al.* (2017), Hofmann and R  sh (2017), Farahani *et al.* (2017), Ghadge *et al.* (2018), and Saberi *et al.* (2019) were utilized. All the items in the scales were measured using a five-point Likert scale, with 1 = strongly disagree to 5 = strongly agree as limits.

Table 1 presents the most relevant characteristics of the sample of 378 manufacturing firms of the Mexican automotive and aerospace industry used in this study, and it is observed that 69% of the firms have more than 10 years in the market; a little more than 40% are medium companies; 72% are non-family businesses, and a little more than 87% are managed for male.

Podsakoff *et al.* (2003) recommended two strategies to address the problems of common response bias through common method bias (CMB). On one hand, managers were informed of the anonymous treatment of their correct and incorrect answers, so they should answer honestly each of the questions posed in the survey. On the other hand, Harman's single factor was used (Podsakoff and Organ, 1986), which establishes that the factor analysis should have a

Table 1. Sample characteristics

Variable	Frequency	Percentage
<i>Firm's Age</i>		
Young companies (<10 years old)	117	31.0
Mature companies (>10 years old)	261	69.0
<i>Total</i>	378	100.0%
<i>Company size</i>		
Small (10–50 employees)	127	33.6
Medium (51–250 employees)	153	40.5
Large (>250 employees)	98	25.9
<i>Total</i>	378	100.0%
<i>Family character</i>		
Family business	106	28.0
Non-family business	272	72.0
<i>Total</i>	378	100.0%
<i>Manager gender</i>		
Male	330	87.3
Female	48	12.7
<i>Total</i>	378	100.0%

common factor that explains at least 50% of the total variance. The results obtained of the exploratory factorial analysis show that $KMO = 0.905$, Bartlett's Test of Sphericity is significant ($X^2 = 8,475.12$, $gl = 231$, $p = 0.000$), and 46.244% of the total variance extracted is explained by a common factor, given that the total extracted factor was less than 50%, it is possible to affirm that there is no CMB problem.

4. Results

Data analysis was carried out using a PLS-SEM. This method allows for understanding causal-predictive power and accounts for the measurement error of variances (Fornell and Larcker, 1981). This technique has gained recognition among researchers, enabling more complex models across various disciplines (Tenenhaus et al., 2005). Hair et al. (2021) identified four critical factors for selecting PLS-SEM: characteristics of the information, characteristics of the model, model estimation, and evaluation. Additionally, by analyzing observed data, predictive analyses provide better explanations of latent variables in areas with emerging theories (Chin et al., 2020; Hair et al., 2021). Now, studies in strategic management would benefit from using PLS-SEM due to its exploratory characteristics, development of new theories, non-parametric data, and others (Hair et al., 2019).

Using the software SmartPLS 4.0 (Ringle et al., 2022), a PLS-SEM was estimated. The use of this estimation is based on two main reasons, first, some authors recommend these statistical techniques in theories that are in a developing phase (Hair et al., 2019) and second, when the objective of the study is to predict or explain concepts in the research model (Sarstedt et al., 219). Additionally, the use of PLS-SEM is also advocated for measuring complex research models involving various variables (Wang et al., 2020; Karami and Madlener, 2021). This approach is recommended not only for assessing structural relationships through confirmatory factor analysis (CFA) and regression but also for dealing with intricate research setups (Ullah et al., 2022).

As a preliminary step for analyzing data derived from the survey conducted with 378 manufacturing firms, the reliability and validity of L4.0, DTI4.0, and LG4.0 scales were assessed. Reliability was measured using Cronbach's Alpha, Dijkstra-Henseler rho, and the Composite Reliability Index (CRI), whereas convergent validity was assessed through the Average Variance Extracted (AVE) (Hair et al., 2019). The results of the PLS-SEM are presented in Table 2. These results indicate that the values of Cronbach's Alpha (0.911; 0.929;

Table 2. Measurement model–reliability, validity and discriminant validity

PANEL A. Reliability and validity					
Variables	Cronbach's Alpha		Dijkstra-Henseler rho	CRI	AVE
Lean 4.0	0.911		0.920	0.938	0.791
Digital technology Industry 4.0	0.929		0.935	0.942	0.684
Logistics 4.0	0.934		0.937	0.944	0.653
PANEL B. Fornell-Larcker criterion					
Variables	1	2	3	Heterotrait–Monotrait ratio (HTMT)	
				1	2
1. Lean 4.0	<i>0.889</i>				
2. Digital Technology Industry 4.0	0.543	<i>0.821</i>		0.524	
3. Logistics 4.0	0.402	0.559	<i>0.808</i>	0.430	0.578
Note(s): 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					

0.934), Dijkstra-Henseler rho (0.920; 0.935; 0.937), and CRI (0.938; 0.942; 0.944) satisfied the recommended threshold of at least 0.70 (Hair and Sarstedt, 2021). The AVE values (0.791; 0.684; 0.653) also surpassed the recommended threshold of at least 0.50 (Hair and Sarstedt, 2021). Therefore, the LM4.0, DTI4.0, and LG4.0 scales were considered reliable and valid, as their values exceeded the literature-recommended thresholds.

Finally, the discriminant validity of the L4.0, DTI4.0, and LG4.0 scales was analyzed using two widely cited and PLS-SEM commonly used indices, i.e. the Fornell and Larcker criterion and the Heterotrait-Monotrait ratio (HTMT) (Henseler, 2018). In essence, the Fornell and Larcker Criterion suggests that the AVE value for each pair of constructs should surpass the correlation between them, while the HTMT recommends a value below 0.85. The results from these indices are detailed in Table 2 (Panel B), revealing that, according to the Fornell and Larcker Criterion, the AVE values significantly exceed the correlation for each construct pair. Additionally, the HTMT values, as recommended, were below 0.85, indicating the discriminant validity for the L4.0, DTI4.0, and LG4.0 scales (Henseler, 2018).

The estimation of the PLS-SEM model showed results that were statistically acceptable. The adjusted R^2 values for the endogenous variables (DTI4.0 = 0.396; LG4.0 = 0.431) satisfied the recommended minimum threshold of 0.10 (Hair et al., 2021). The SRMR ranking is under the recommended value (0.080), as well as the HI99 values (0.045; 0.056). Moreover, the unweighted least squares discrepancy (dULS) values (0.940–0.970) and the geodesic discrepancy (dG) values (0.823–0.853) were below the HI99 values recommended by Sarstedt et al. (2019). Lastly, the effect sizes of the independent variables (f^2) on the adjusted R^2 values of the dependent variable suggested the presence of small variations (Hair et al., 2017). The results are presented in Table 3.

The estimated data presented in Table 3 corroborate the argument that L4.0 has a significant positive effect on both LG4.0 (0.139; p -value 0.009) and DTI4.0 (0.544; p -value 0.000). These results provide robust empirical evidence supporting hypotheses H1 and H2, indicating that the adoption of L4.0 leads to the successful activities of both LG4.0 and DTI4.0 in the manufacturing firms of the automotive and aerospace industries in Mexico. Additionally, the results from the data estimation also validate our assertion that DTI4.0 has a positive effect on

Table 3. Structural model

Paths	Path (t-value; p -value)	95% confidence interval	f^2	Supported
L4.0 → LG4.0 (H1)	0.139 (2.625; 0.009)	[0.034–0.244]	0.017	Yes
L4.0 → DTI4.0 (H2)	0.544 (14.080; 0.000)	[0.463–0.614]	0.429	Yes
DTI4.0 → LG4.0 (H3)	0.488 (10.821; 0.000)	[0.391–0.566]	0.257	Yes
<i>Indirect Effects</i>				
L4.0 → DTI4.0 → LG4.0 (H4)	0.265 (9.180; 0.000)	[0.212–0.324]		Yes
Endogenous Variable	Adjusted R^2	Model Fit SRMR	Value	HI99
DTI4.0	0.396	dULS	0.940	0.970
LG4.0	0.431	dG	0.823	0.853
Note(s): L4.0: Lean 4.0; DTI4.0: Digital Technology Industry 4.0; LG4.0: Logistics 4.0. 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: bootstrap-based 99% percentiles				

LG4.0 (0.488; *p-value* 0.000), providing strong empirical evidence supporting hypothesis H3. The adoption of DTI4.0 results in an enhancement of the LG4.0 activities in the manufacturing firms of the automotive and aerospace industries in Mexico.

Lastly, the model results confirm our argument that DTI4.0 plays a mediating role in the link between L4.0 and LG4.0 activities (0.265; *p-value* 0.000). These values strongly support hypothesis H4, demonstrating that a crucial part of the positive effect generated by L4.0 on LG4.0 activities in the manufacturing firms of the automotive and aerospace industries in Mexico is transferred through the application of DTI4.0. In this context, we can conclude that the adoption and application of DTI4.0 in companies not only enhances LG4.0 activities but also acts as an essential mediator variable, assisting manufacturing firms in significantly increasing the outcomes of the link between L4.0 and LG4.0 activities.

To assess the extent to which the final model presented in Table 3 can be generalized to the broader population (i.e. manufacturing firms in Mexico's automotive and aerospace industries), the model's predictive power was evaluated using PLSpredict. The results of this analysis are shown in Table 4 below.

Table 4 shows that the $Q^2_{predict}$ values for the dependent variables are positive, and the mean prediction errors from the PLS-SEM are nearly zero (Digital Technology Industry 4.0 $Q^2_{predict}$ = 0.287, PLS-SEM prediction error = -0.001; Logistics 4.0 $Q^2_{predict}$ = 0.154, PLS-SEM prediction error = -0.001), indicating that the final measurement model has a strong predictive power.

5. Discussion

The results obtained from the analyses presented in Section 4 support our argument that L4.0 has a positive impact on the LG4.0 activities of manufacturing firms in the automotive and aerospace industries in Mexico. These results are in line with those found by De Felice *et al.* (2018), Melo *et al.* (2020), and Alfonso *et al.* (2021). The key reasons behind this positive effect include managers' awareness of the various benefits resulting from the adoption of L4.0. These benefits encompass the elimination of non-value-added production processes, leading to increased production and organizational productivity. However, to avoid the loss of these initial achievements, manufacturing firms in the automotive and aerospace industries must improve their soft and hard L4.0 practices, since this will help organizations achieve sustainable results over the long term by adopting LG4.0 practices.

Furthermore, the results also support our argument that L4.0 has a positive impact on DTI4.0 in the automotive and aerospace industries in Mexico. This aligns with findings from Shahin *et al.* (2020), Rosin *et al.* (2020), and Tortorella *et al.* (2021b). Fundamental reasons explaining this positive impact include not only the high synergy between L4.0 and DTI4.0 (Pagliosa *et al.*, 2021), but also the tangible benefits arising from the link between L4.0 and DTI4.0, such as reduced industrial waste, lower inventory levels, product distribution and delivery times, contributes to the positive impact. These findings contribute to the nascent debate on how L4.0 and DTI4.0 concepts interact and how their relationship leads to improved business outcomes (Gillani *et al.*, 2020; Tortorella *et al.*, 2021b).

Table 4. PLS-SEM $Q^2_{predict}$ and prediction error (descriptives)

	$Q^2_{predict}$	Mean	Median	Observed Min.	Observed Max.	Cramér-von Mises test Statistics	Cramér-von Mises <i>p-value</i>
Digital technology Industry 4.0	0.287	-0.001	0.161	-2.995	1.757	11.049	0.000
Logistics 4.0	0.154	-0.001	0.031	-3.588	2.593	3.041	0.000

Moreover, the results of this study not only suggest that I4.0 has a positive effect on LG4.0 activities, in line with findings from [Torbacki and Kijewska \(2019\)](#), [Sun et al. \(2022\)](#), and [Parhi et al. \(2022\)](#), but also that it can act as a mediating role in the relationship between DTL4.0 and LG4.0; this is also consistent with results by [Parhi et al. \(2022\)](#), [Qureshi et al. \(2023\)](#), and [Rahardjo et al. \(2023\)](#). This finding may be explained through the management capabilities of executives in the automotive and aerospace manufacturing industries, as the transition to L4.0 and DTI4.0 requires the integration of all organizational activities, especially the digitalization of logistics activities, which will allow them to improve both business results and the technological digitalization of L4.0 and LG4.0 activities.

5.1 Practical implications

The findings of this study carry various practical implications not only for managers and manufacturing firms in the automotive and aerospace industries but also for policymakers. One initial implication is that manufacturing companies in the automotive and aerospace industries take advantage of the potential that digital technologies have in their improvement efforts, not only by merging into a broader strategy such as L4.0 ([Tortorella et al., 2021a](#)), or well as LG4.0 ([Dallasega et al., 2022](#)), better business results can be achieved in the long term. However, to achieve these results, manufacturing firms must generate training programs for their staff, not only so that they accept these new digital technologies, but also so that they improve their skills and knowledge in the use of digital technologies.

A second practical implication is that from a digital technology perspective, L4.0 can be a crucial driver for the technological advancement of manufacturing firms in the automotive and aerospace industries, not only in production processes but also in LG4.0 activities. In this sense, is essential for manufacturing firms to top management to define what is the objective that the organization is willing to achieve, instead of what is technically feasible to achieve with the DTI4.0, since the alignment of the desired improvement goals with the mechanisms that each one allows of DTI4.0 in both L4.0 and LG4.0 activities, could generate better long-term business results, as well as better use of digital technologies.

Lastly, a third practical implication is that the adoption of L4.0, DTI4.0, and LG4.0 underscores the need for advanced communication between personnel and technological tools. Within this context, governments and policymakers must provide the infrastructure and necessary policies to expedite the preparation of workers for the adoption and application of L4.0, DTI4.0, and LG4.0. Also, academic institutions will need to review their undergraduate and graduate programmes to ensure that graduates have the technical skills and knowledge necessary for the use and management of the DTI 4.0. However, the policies and training programs for personnel of manufacturing firms in the automotive and aerospace industries must establish that DTI 4.0 are clearly a means to an end, not an end in itself.

6. Conclusions, limitations and future research

The results of this study yield various key conclusions, with some of the most essential deductions outlined below. Firstly, a robust correlation among L4.0, DTI4.0, and LG4.0 can be inferred. This indicates that the research model employed in this study demonstrates acceptable internal consistency by offering a holistic view of the core elements of L4.0, DTI4.0, and LG4.0 activities as established in the literature. Notably, there is a scarcity of prior literature focusing on the simultaneous analysis of these three concepts and providing empirical evidence. Therefore, in future studies, it would be interesting to analyze what type of digital technologies have the best results in both L4.0 and LG4.0 activities, as well as which L4.0 tools best integrate digital technologies and generate better business results.

Secondly, the increasing integration of digital technologies in companies, accompanied by rapid shifts in the global business landscape, presents a range of challenges for organizations. The profound pressure on manufacturing firms to adapt to these global changes for survival

and revenue enhancement is placing numerous enterprises at risk, especially in emerging economies. Therefore, in future studies, it will be necessary to analyze whether the DTL4.0, I4.0 and LG4.0 practices can identify the industrial and digital waste that manufacturing firms in the automotive and aerospace industries have, and what digital technologies are not only to identify the main solutions, but also to improve business results and long-term sustainability.

Despite the robust methodological approach followed by this study, it still has several limitations that need to be considered when interpreting the results. A primary limitation is the sample used, focusing solely on large and medium manufacturing companies in the automotive and aerospace industries. Future studies may find it valuable to include micro-manufacturing companies with fewer than 10 employees to explore potential differences in the results. Another limitation is that the analyses were based merely on data obtained from a survey of managers in manufacturing companies. Future studies could consider the opinions of suppliers to determine if the results align with those obtained in this study. Finally, a third limitation is that the data analysis focused on cross-sectional information, overlooking the potential temporal effects of L4.0, DTI4.0, and LG4.0. Future studies may find it worthwhile to conduct longitudinal studies to explore temporal dynamics.

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