

Lean–Industry 4.0 Synergy in the Moroccan Automotive Sector: A PLS-SEM Analysis of Organisational and Competitive Performance

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Abstract

This study examines Lean Management–Industry 4.0 integration in the Moroccan automotive sector using partial least squares structural equation modelling (PLS-SEM) and survey data from 263 managers and professionals involved in Lean and/or Industry 4.0 implementation. The results show that Lean–Industry 4.0 integration is not directly associated with significantly higher continuous process improvement and production flexibility. Organisational and cultural challenges are negatively associated with these outcomes, whereas training and change-management capabilities are positively associated with them. Continuous process improvement and production flexibility are, in turn, positively associated with competitive advantage. Complementary structural relationships further show that technological integration, implementation complexity, training, and organisational challenges coexist within the broader transformation process. These findings support a socio-technical interpretation in which organisational and human capabilities accompany technological integration and are associated with continuous-improvement outcomes.

From an applied economic perspective, the findings suggest that capability development and continuous improvement may contribute to more efficient use of labour and installed capital and, when diffused across firms and suppliers, may support productivity upgrading, regional value creation, and the attractiveness of Moroccan automotive industrial zones to foreign direct investment. These broader economic effects are interpreted as implications of the firm-level results rather than as directly estimated macroeconomic effects. Policy implications therefore emphasize combining Industry 4.0 investment incentives with workforce training, organisational-readiness measures, supplier development, and measurable productivity targets.

Keywords: lean management, industry 4.0, lean 4.0, automotive industry, organisational capabilities, competitive advantage, PLS-SEM.

JEL Classification: L23; O14; O31; O33; O47.

Introduction

The digital transformation of industrial systems, driven by Industry 4.0 technologies, is redefining the paradigms of production, management, and competitiveness in manufacturing companies. This technological revolution, based on the integration of the Internet of Things (IoT), cyber-physical systems, artificial intelligence, and advanced automation, aims to create smart, interconnected, and adaptive factories (Kagermann et al., 2013; Liao et al., 2017).

At the same time, Lean Management, rooted in the principles of waste reduction, standardization, and continuous improvement, remains a pillar of operational excellence. It has proven effective in streamlining processes, optimizing flows, and increasing customer value (Womack and Jones, 1996; Shah and Ward, 2007). The convergence between these two paradigms, often referred to as Lean 4.0, is attracting growing interest in scientific literature. Several researchers point out that Industry 4.0 technologies can strengthen Lean tools by automating routines, improving traceability, facilitating real-time decision-making, and supporting continuous improvement dynamics (Frank et al., 2024; Tortorella and Fettermann, 2018; Buer et al., 2018). However, this synergy does not come about automatically: it requires profound organisational transformation, strategic alignment, and investment in human skills and digital infrastructure (Sony and Naik, 2020).

Recent research increasingly emphasizes that the integration of Lean and Industry 4.0 should not be viewed solely as a technological transformation, but rather as a socio-technical process involving operational practices, digital technologies, and human factors (Frank et al., 2024). Moreover, empirical evidence suggests that Lean and Industry 4.0 may generate different and complementary effects on operational performance and worker-related outcomes (Frank et al., 2025).

In the Moroccan automotive sector, where Lean approaches are already well established, the integration of Industry 4.0 technologies represents both a strategic opportunity and a transformation challenge. The objective of this article is to empirically analyse this synergy through partial least squares structural equation modelling (PLS-SEM), focusing exclusively on the quantitative component of the study. The approach enables the assessment of a conceptual model integrating six key dimensions to examine how Lean–Industry 4.0 integration, organisational conditions, human capabilities, and technological complexity are associated with continuous improvement and competitive advantage.

2. Literature Review and Hypotheses Development

In order to empirically model the relationships between Lean practices, Industry 4.0 technologies, and organisational performance, this study draws on a set of theoretical hypotheses formulated from recent scientific literature. These hypotheses reflect the presumed mechanisms through which Lean–Industry 4.0 synergy influences the internal dynamics of industrial companies, particularly in terms of flexibility, responsiveness, competitiveness, and innovation.

They take into account the levers identified in the work of Frank et al. (2024), Buer et al. (2018), and Tortorella and Fettermann (2018), which emphasize the importance of alignment between technological, human, and organisational dimensions for successful digital transformation in Lean environments. They also incorporate potential barriers related to technological complexity, implementation costs, and cultural resistance, as suggested by the research of Sony and Naik (2020) and Wiese et al. (2024).

2.1. Economic Grounding of the Constructs

In this study, operational performance is viewed not only as an organisational outcome but also as a firm-level manifestation of economic productivity. Improvements in cycle time, defect reduction, flow stability, equipment utilization, and waste elimination can enhance labour productivity by increasing output per worker and can improve capital efficiency by generating greater output from the existing stock of industrial assets. When these organisational and technological efficiency gains are sustained, they may also contribute to improvements in total factor productivity (TFP), as performance gains arise from better knowledge, coordination, process design, and data utilization rather than from a proportional increase in labour or capital inputs. Accordingly, the continuous-improvement (ACP) and competitive-advantage (ASCLI40) constructs can be interpreted as operational mechanisms through which Lean–Industry 4.0 may strengthen firm-level productivity and competitiveness, thereby providing a microeconomic foundation for potential improvements in TFP.

Innovation is also considered here as an economic mechanism supporting productivity growth and competitive renewal, rather than being limited to the introduction of new products or processes. From a Schumpeterian perspective, Lean–Industry 4.0 promotes new combinations of technologies, organisational routines, and capabilities, thereby creating new ways of producing, organising, and competing. From the perspective of endogenous growth theory, continuous training, organisational learning, and digital capabilities can be regarded as forms of knowledge capital that accumulate within firms and may generate persistent productivity gains and knowledge spillovers. From a dynamic capabilities perspective, successful Lean–Industry 4.0 integration requires firms to continuously reconfigure organisational resources, develop new competencies, and adapt operational practices to technological and environmental changes (Komkowski et al., 2025). This interpretation is consistent with evidence showing that innovation can reinforce export performance (Carboni and Medda, 2024) and with recent manufacturing research indicating that the outcomes of Lean–Industry 4.0 depend on the interaction between technology, employees, and organisational capabilities (Frank et al., 2024; Frank et al., 2025; Komkowski et al., 2025).

2.2. Hypotheses Development

The integration of Lean Management and Industry 4.0 represents a socio-technical transformation in which technological capabilities interact with established operational practices, organisational conditions, and human capabilities. Previous research indicates that Industry 4.0 technologies can reinforce Lean practices by improving traceability, automation, real-time information availability, process monitoring, and decision-making, while lean provides the organisational and operational foundation required to translate technological capabilities into performance improvements (Buer et al., 2018; Tortorella and Fettermann, 2018; Frank et al., 2024). At the same time, the benefits of this integration are not automatic, as technological, organisational, and human factors can either facilitate or constrain the resulting improvement dynamics (Sony and Naik, 2020; Frank et al., 2024; Komkowski et al., 2025).

In addition to the five theoretically specified hypothesis paths, the final structural model examines four complementary relationships: ILI40 → CTC, CTC → DOC, FCAC → CTC, and FCAC → DOC. These relationships are included to provide additional insight into how technological integration, implementation complexity, training and change-management capabilities, and organisational conditions interact within the Lean–Industry 4.0 transformation

process. As these relationships were not formulated as separate a priori hypotheses, they are treated as complementary structural associations rather than confirmatory hypotheses.

Lean Management is based on waste reduction, process standardization, flow optimization, and continuous improvement, whereas Industry 4.0 provides technological capabilities such as real-time data collection, connectivity, automation, and advanced process monitoring. Their integration can therefore enhance the visibility and responsiveness of production processes and strengthen established Lean practices.

Previous research has identified important complementarities between Lean Management and Industry 4.0. Buer et al. (2018) show that the two paradigms can interact through multiple operational mechanisms, while Tortorella and Fettermann (2018) provide empirical evidence concerning the association between Lean production practices and Industry 4.0 adoption. More recent studies emphasize that digital technologies can reinforce Lean practices when technological implementation is appropriately integrated with operational processes and organisational capabilities (Frank et al., 2024). Similarly, Hossain and Purdy (2023) and Rahardjo et al. (2023) highlight the potential of Lean–Industry 4.0 integration to support manufacturing performance and continuous-improvement practices.

On this basis, the study proposes:

H1. Lean–Industry 4.0 integration is positively associated with continuous process improvement and production flexibility.

The integration of Lean practices and Industry 4.0 technologies requires changes not only in production technologies but also in organisational routines, employee roles, coordination mechanisms, and managerial practices. Resistance to change, insufficient internal digital capabilities, weak interdepartmental collaboration, and organisational rigidity may therefore constrain the ability of firms to translate technological investments into continuous operational improvement.

Sony and Naik (2020) identify organisational readiness and human capabilities among the critical factors affecting Industry 4.0 implementation. Wiese et al. (2024) further emphasize the relevance of organisational culture to the use of Industry 4.0 technologies, while Margherita and Braccini (2024) highlight tensions that may emerge when digital technologies are introduced into established Lean production systems. From a dynamic-capabilities perspective, successful Lean–Industry 4.0 integration also depends on the ability of firms to adapt organisational routines, capabilities, and workforce practices to technological change (Komkowski et al., 2025).

Organisational and cultural barriers may consequently weaken continuous-improvement dynamics even when technological resources are available. Therefore:

H2. Organisational and cultural challenges are negatively associated with continuous process improvement in Lean–Industry 4.0 environments.

The transition toward digitally enabled Lean production requires employees and managers to develop new technical, analytical, and organisational capabilities. Continuous training can facilitate the effective use of digital technologies, while structured change-management practices can reduce resistance, strengthen employee participation, and support the adaptation of existing Lean routines to new technological environments.

Frank et al. (2024) conceptualize Lean–Industry 4.0 integration as an interaction between Lean practices, digital technologies, and people rather than as an exclusively technological transformation. Margherita and Braccini (2024) similarly emphasize the organisational tensions associated with digital transformation in Lean production systems. From the dynamic-capabilities perspective, firms must continuously develop and reconfigure skills, resources, and organisational capabilities to respond effectively to technological change (Komkowski et al., 2025).

Training and organisational learning can therefore be understood as forms of firm-specific human and knowledge capital that facilitate the conversion of digital investment into operational improvements. This interpretation is also consistent with evidence that the digitalization of human-resource practices can generate measurable labour-productivity gains (Vader et al., 2025). Accordingly:

H3. Training and change-management capabilities are positively associated with continuous process improvement in Lean–Industry 4.0 environments.

Despite the potential benefits associated with Industry 4.0, its implementation may involve substantial technological and financial challenges. Firms may face high acquisition and integration costs, technical complexity, uncertainty regarding short-term returns on investment, difficulties in adapting existing Lean tools to digital environments, and limited access to specialized technological expertise.

These barriers are particularly relevant when digital technologies must be integrated into established Lean production systems rather than implemented independently. Sony and Naik (2020) identify technological and organisational readiness among the critical conditions for Industry 4.0 implementation, while Bahulikar et al. (2023) address the integration of Lean thinking and Industry 4.0 and the implementation conditions associated with this transition. Such constraints can absorb managerial and financial resources, complicate process redesign, and reduce the extent to which digitalization contributes to continuous operational improvement.

Accordingly:

H4. Technological complexity and implementation costs are negatively associated with continuous process improvement in Lean–Industry 4.0 environments.

Continuous improvement constitutes one of the central mechanisms through which Lean practices can generate sustained organisational benefits. Improvements in production flexibility, process responsiveness, real-time performance monitoring, cycle-time reduction, waste elimination, and the reallocation of labour toward higher value-added activities can enhance the firm's ability to respond to changing market requirements.

The integration of Industry 4.0 technologies can reinforce these mechanisms by increasing information availability, process transparency, and the capacity for rapid operational adjustment. Utiyama et al. (2025) emphasize the role of integrated Lean and Industry 4.0 approaches in operational improvement, while Saraswat et al. (2025) associate the technological integration of Lean and Industry 4.0 with the development of more advanced and responsive production systems. Recent evidence also indicates that Lean and Industry 4.0 can generate distinct but complementary effects on operational performance (Frank et al., 2025).

From an economic perspective, continuous process improvement can contribute to competitive advantage by increasing labour productivity, improving the efficiency of installed capital, reducing non-quality costs and waste, and strengthening innovation and responsiveness. These firm-level capabilities may support stronger competitive positioning without requiring proportional increases in productive inputs. Innovation and organisational capability development can additionally reinforce firms' competitive and export performance (Carboni and Medda, 2024; Komkowski et al., 2025). Therefore:

H5. Continuous process improvement and production flexibility are positively associated with competitive advantage.

3. Methodological Framework

3.1. Methodological Approach

This study adopts a post-positivist quantitative research approach and applies partial least squares structural equation modelling (PLS-SEM) to examine the hypothesized relationships among the organisational, technological, and operational dimensions of Lean–Industry 4.0 integration in the Moroccan automotive sector.

PLS-SEM was selected because the proposed model comprises multiple interconnected latent constructs and seeks to evaluate both the measurement properties of these constructs and the structural relationships among them. The method is particularly suitable for research models that integrate technological, organisational, and human dimensions and emphasize explanation and prediction of complex relationships among latent variables (Hair et al., 2022). The Lean–Industry 4.0 context is consistent with this methodological orientation because recent research conceptualizes industrial digital transformation as a complex socio-technical process involving Lean practices, digital technologies, organisational capabilities, and human factors (Frank et al., 2024).

PLS-SEM also enables the simultaneous assessment of the measurement and structural models. In the present study, the measurement model evaluates the reliability and validity of six reflective latent constructs, whereas the structural model examines the theoretically specified relationships among Lean–Industry 4.0 Integration (ILI40), Organisational and Cultural Challenges (DOC), Training and Change Management (FCAC), Technological Complexity and Costs (CTC), Continuous Process Improvement and Production Flexibility (ACP), and Competitive Advantage (ASCLI40).

The empirical analysis is based on 263 respondent-level observations. PLS-SEM can provide reliable estimates under a range of sample-size conditions and does not require the strict multivariate normality assumptions associated with some covariance-based structural equation modelling procedures (Henseler et al., 2009; Sarstedt et al., 2017). However, the selection of PLS-SEM in this study is primarily motivated by the predictive orientation and structural complexity of the research model rather than by sample size alone.

Accordingly, PLS-SEM is used to assess the reliability and validity of the measurement constructs and to estimate the hypothesized structural associations among the latent variables. The analysis therefore identifies statistically supported relationships within the proposed theoretical model but does not, given the cross-sectional research design, establish causal effects.

3.2. Operationalization of Constructs

The operationalization of the latent constructs followed established principles of measurement-scale development and adaptation, drawing on the methodological framework proposed by Churchill (1979) and subsequently developed in marketing and management research by Évrard et al. (2009). The measurement items were adapted from previously validated empirical studies in Lean manufacturing, Industry 4.0, industrial digitalization, organisational transformation, and operational performance.

The questionnaire comprised 29 measurement items across six reflective latent constructs. Following measurement-model assessment, one indicator (ILI401) was removed because of insufficient indicator reliability, resulting in a final measurement model comprising 28 retained indicators. These constructs correspond directly to the conceptual framework and hypotheses developed in Section 2.2: Lean–Industry 4.0 Integration (ILI40), Organisational and Cultural Challenges (DOC), Training and Change Management (FCAC), Technological Complexity and Costs (CTC), Continuous Process Improvement and Production Flexibility (ACP), and Competitive Advantage (ASCLI40).

Lean–Industry 4.0 Integration (ILI40) was initially operationalized using four measurement items. Following measurement-model assessment, ILI401 was removed because of its low outer loading (0.415), leaving ILI402, ILI403, and ILI404 as the three indicators retained in the final model. Its four measurement items were informed by Hossain and Purdy (2023) and Rahardjo et al. (2023), with particular emphasis on the integration of Lean tools with digital technologies, production-flow management, traceability, connectivity, and process efficiency.

Organisational and Cultural Challenges (DOC) are measured through five items addressing resistance to change, internal skills, interdepartmental coordination, organisational barriers, and organisational culture. The construct was developed with reference to Wiese et al. (2024), Margherita and Braccini (2024), and Frank et al. (2024), which emphasize the organisational and human dimensions of Lean–Industry 4.0 transformation.

Training and Change Management (FCAC) comprise five items reflecting continuous training, employee involvement, managerial commitment, organisational learning, and structured change-management practices. These dimensions are likewise grounded in the work of Wiese et al. (2024), Margherita and Braccini (2024), and Frank et al. (2024), which underline the importance of human capabilities and organisational adaptation in industrial digital transformation.

Technological Complexity and Costs (CTC) are operationalized through five items addressing implementation costs, adaptation requirements, technical complexity, uncertainty regarding returns on investment, and access to specialized technological expertise. This construct was primarily informed by Bahulikar et al. (2023).

Continuous Process Improvement and Production Flexibility (ACP) are measured through five items capturing production flexibility, cycle-time reduction, digital support for continuous improvement, real-time decision-making, and the reallocation of labour toward higher value-added activities. The operationalization of this construct was informed by Utiyama et al. (2025).

Finally, Competitive Advantage (ASCLI40) is represented by five items reflecting cost-related competitiveness, operational efficiency, customer satisfaction, innovation, market positioning, and organisational agility. The construct was operationalized with reference to Saraswat et al. (2025).

Table 1 summarizes the constructs, number of measurement items, and principal literature sources used for their operationalization. The complete questionnaire and wording of all 29 measurement items are provided in Appendix A.

Table 1. Operationalization of the Study Constructs

Construct	Code	No. of items	Main sources
Lean–Industry 4.0 Integration	ILI40	4	Hossain & Purdy (2023); Rahardjo et al. (2023)
Organisational and Cultural Challenges	DOC	5	Wiese et al. (2024); Margherita & Braccini (2024); Frank et al. (2024)
Training and Change Management	FCAC	5	Wiese et al. (2024); Margherita & Braccini (2024); Frank et al. (2024)
Technological Complexity and Costs	CTC	5	Bahulikar et al. (2023)
Continuous Process Improvement and Production Flexibility	ACP	5	Utiyama et al. (2025)
Competitive Advantage	ASCLI40	5	Saraswat et al. (2025)

Note: The questionnaire contained 29 items. ILI401 was removed during measurement-model assessment; consequently, 28 indicators were retained in the final PLS-SEM model.

3.3. Population and Sampling

The target population of this study consists of managers and professionals working in companies operating in Morocco's automotive sector and directly involved in production, continuous improvement, quality, maintenance, digital transformation, or related operational functions. The Moroccan automotive industry represents a strategically important manufacturing sector characterized by strong integration into international value chains and increasing exposure to Lean Management practices and Industry 4.0 technologies.

The empirical sample comprises 263 respondents occupying middle- and senior-management or specialist positions. Participants were selected using a non-probability purposive sampling approach, complemented by snowball sampling. The initial questionnaire distribution targeted managers and professionals who met the study's eligibility criteria, particularly those directly involved in Lean practices and/or Industry 4.0 technologies. Some initial contacts and respondents subsequently redistributed the questionnaire within their professional networks to other eligible professionals working in the same industrial field.

Eligibility was based on respondents' direct involvement in the implementation of Lean practices, including 5S, Kaizen, SMED, Kanban, TPM, and related continuous-improvement tools, and/or in the adoption of Industry 4.0 technologies, such as Manufacturing Execution Systems (MES), the Internet of Things (IoT), collaborative robotics, industrial automation, and industrial data platforms. This respondent profile was considered appropriate because the study investigates organisational, technological, and human factors that require direct operational or managerial knowledge of Lean–Industry 4.0 implementation.

The sample covers respondents from different automotive-related activities, including wiring, plastics, textiles, mechanics, electrical activities, and other industrial segments, as well as companies of different workforce sizes. This diversity enables the study to capture perceptions across a heterogeneous industrial environment rather than from a single organisational category.

Because the questionnaire was further redistributed through respondents' professional networks, the total number of individuals who ultimately received the questionnaire was not formally recorded. Consequently, a reliable response rate cannot be calculated. Similarly, the data-collection process did not formally record the number of distinct companies represented by the 263 respondents. More than one respondent could therefore originate from the same company, but the number of respondents per company and the extent of within-company clustering cannot be determined retrospectively. These characteristics should be considered when interpreting the representativeness and generalizability of the findings.

3.4. Data Collection

Data were collected using a structured online questionnaire administered through Google Forms between August 2024 and May 2025. The instrument was designed to capture both respondent and organisational characteristics and perceptions regarding the integration of Lean Management practices with Industry 4.0 technologies in the Moroccan automotive sector. The questionnaire was initially distributed to managers and professionals who met the study's eligibility criteria, particularly those involved in Lean practices and/or Industry 4.0 implementation. Consistent with the purposive and snowball sampling approach described in Section 3.3, some initial contacts and respondents subsequently redistributed the questionnaire within their professional networks to other eligible professionals working in the same industrial field.

The questionnaire consisted of two sections. The first collected general information on the respondents and their organisational context, including gender, the company's field of activity within the automotive sector, and workforce size. The second section comprised 29 measurement items organised into six dimensions: (1) Lean–Industry 4.0 Integration; (2) Organisational and Cultural Challenges; (3) Training and Change Management; (4) Technological Complexity and Implementation Costs; (5) Continuous Process Improvement and Production Flexibility; and (6) Competitive Advantage.

All perception items were measured using a five-point Likert scale, ranging from 1 = strongly disagree to 5 = strongly agree. Prior to full administration, the questionnaire was pre-tested with industry experts to assess the clarity, relevance, and comprehensibility of the measurement items. The instrument incorporated established concepts and practices from the Lean Management and Industry 4.0 literature while adapting the items to the operational context of the Moroccan automotive industry.

A total of 263 usable responses were retained for the empirical analysis. Because the questionnaire was subsequently redistributed through professional networks, the total number of individuals who ultimately received the questionnaire was not formally recorded. Therefore, a reliable response rate could not be calculated retrospectively.

The complete measurement instrument, including respondent characteristics, construct definitions, item codes, and individual questionnaire statements, is provided in *Appendix A*.

4. PLS-SEM Analysis

4.1. Conceptual Model

The conceptual model was developed to examine the structural relationships through which Lean–Industry 4.0 integration and associated organizational, human, and technological conditions are related to continuous process improvement and competitive advantage in the Moroccan automotive sector. The model comprises six reflective latent constructs:

- Lean–Industry 4.0 Integration (ILI40),
- Organisational and Cultural Challenges (DOC),
- Training and Change Management (FCAC),
- Technological Complexity and Costs (CTC),
- Continuous Process Improvement and Production Flexibility (ACP), and
- Competitive Advantage (ASCLI40).

The model adopts a sequential structure rather than treating all constructs as independent antecedents of a single outcome. Lean–Industry 4.0 Integration (ILI40) represents the technological–operational integration dimension, while Organisational and Cultural Challenges (DOC), Training and Change Management (FCAC), and Technological Complexity and Costs (CTC) capture organisational, human, and implementation conditions associated with Lean–Industry 4.0 transformation. Continuous Process Improvement and Production Flexibility (ACP) represents the principal intermediate operational outcome, whereas Competitive Advantage (ASCLI40) constitutes the final outcome construct.

Consistent with the hypotheses developed in Section 2.2, the confirmatory component of the structural model evaluates five theoretically specified relationships:

- Lean–Industry 4.0 Integration with Continuous Process Improvement and Production Flexibility (ILI40 → ACP; H1);
- Organisational and Cultural Challenges with Continuous Process Improvement and Production Flexibility (DOC → ACP; H2);
- Training and Change Management with Continuous Process Improvement and Production Flexibility (FCAC → ACP; H3);
- Technological Complexity and Costs with Continuous Process Improvement and Production Flexibility (CTC → ACP; H4); and
- Continuous Process Improvement and Production Flexibility with Competitive Advantage (ACP → ASCLI40; H5).

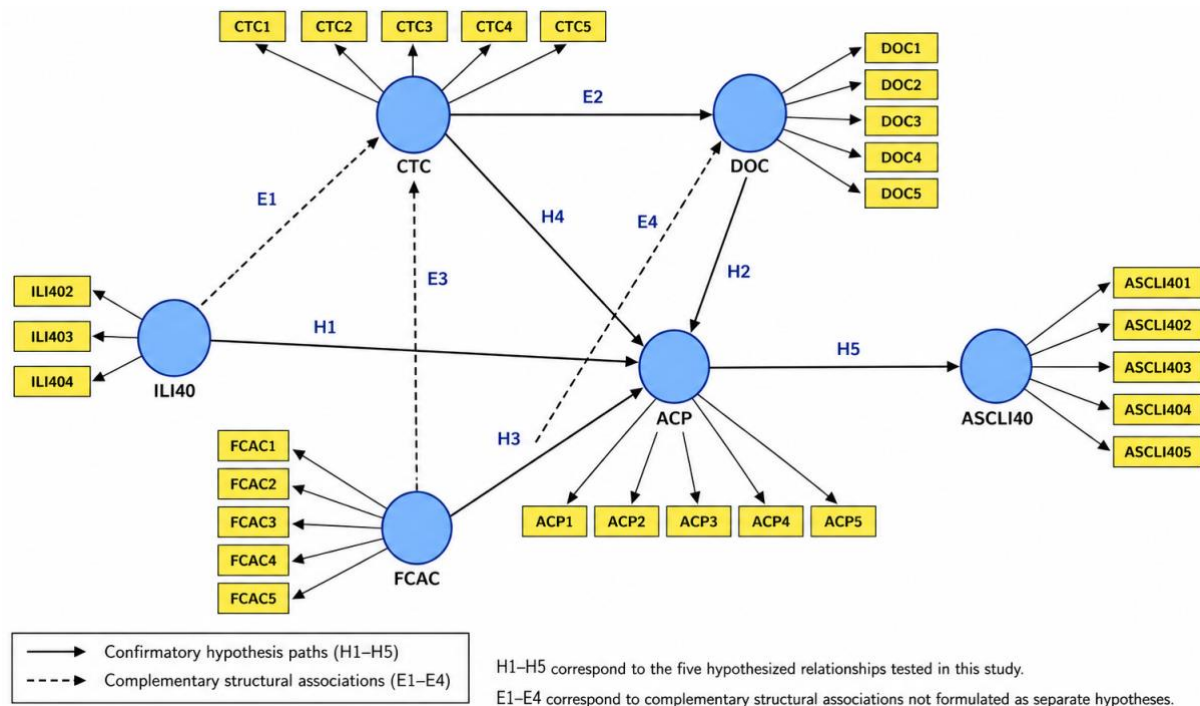
In addition to these five hypothesized relationships, the final structural model includes four complementary structural associations:

- Lean–Industry 4.0 Integration with Technological Complexity and Costs (ILI40 → CTC; E1),
- Technological Complexity and Costs with Organisational and Cultural Challenges (CTC → DOC; E2),
- Training and Change Management with Technological Complexity and Costs (FCAC → CTC; E3), and
- Training and Change Management with Organisational and Cultural Challenges (FCAC → DOC; E4).

These relationships are included to provide a more complete representation of the interactions among technological integration, implementation complexity, organisational conditions, and human capabilities within the estimated model. Because they were not formulated as separate hypotheses in Section 2.2, they are treated as complementary structural associations rather than confirmatory hypotheses.

Accordingly, the final model distinguishes between theoretically specified hypothesis testing and complementary structural analysis. This distinction is maintained throughout the subsequent structural-model assessment and Discussion to avoid interpreting relationships not established a priori as confirmatory evidence. Figure 1 presents the final structural specification evaluated using PLS-SEM.

Figure 1. Final PLS-SEM Conceptual Model



Source: Authors' elaboration based on the final SmartPLS model.

4.2. Evaluation of the Measurement Model

The measurement model was evaluated before assessing the structural relationships among the latent constructs. Because all six constructs were specified as reflective, the assessment focused on indicator reliability, internal consistency reliability, convergent validity, discriminant validity, and indicator-level collinearity.

The questionnaire initially comprised 29 measurement items across the six constructs. During measurement-model assessment, ILI401, originally associated with Lean–Industry 4.0 Integration (ILI40), was removed because of its low outer loading (0.415). Consequently, the final measurement model retained 28 indicators, with ILI40 measured by ILI402, ILI403, and ILI404. All subsequent measurement- and structural-model results reported in this study refer to this final specification.

Internal consistency reliability was assessed using Cronbach's alpha (α), rho_A, and composite reliability (rho_C). The final SmartPLS results indicate satisfactory reliability across all six constructs. Cronbach's alpha values range from 0.759 for ILI40 to 0.886 for DOC, while composite reliability (rho_C) ranges from 0.861 to 0.914. All values exceed the commonly recommended threshold of 0.70, supporting satisfactory internal consistency reliability.

Convergent validity was assessed using the Average Variance Extracted (AVE). AVE values range from 0.608 for ACP to 0.682 for ASCLI40, and all constructs exceed the recommended threshold of 0.50. The results therefore indicate that each construct explains more than half of the variance of its retained indicators, supporting convergent validity.

Table 2 summarizes the reliability and convergent-validity results for the six reflective constructs in the final measurement model.

Table 2. Construct Reliability and Convergent Validity

Construct	Cronbach's α	rho_A	rho_C	AVE
ACP	0.838	0.843	0.886	0.608
ASCLI40	0.882	0.885	0.914	0.682
CTC	0.877	0.881	0.910	0.670
DOC	0.886	0.932	0.914	0.680
FCAC	0.875	0.875	0.910	0.669
ILI40	0.759	0.775	0.861	0.674

Note: Values correspond to the final SmartPLS measurement model after removal of ILI401.

Indicator reliability was assessed using the outer loadings obtained from the final PLS-SEM algorithm. ILI401 was removed during measurement-model assessment because of its low outer loading (0.415). Following its removal, all 28 indicators retained in the final model exhibited outer loadings above 0.70, ranging from 0.716 for ACP3 to 0.881 for DOC4, indicating satisfactory indicator reliability (Hair et al., 2019; 2022).

Indicator-level collinearity was assessed using the variance inflation factor (VIF). VIF values ranged from 1.445 for ACP3 to 3.000 for DOC3, remaining within acceptable levels and indicating no problematic collinearity among the indicators. The final outer loadings and indicator-level VIF statistics are reported in Table 3.

Table 3. Outer Loadings and Indicator-Level Collinearity Statistics

Construct	Indicator	Outer Loading	VIF
ACP	ACP1	0.763	1.874
	ACP2	0.842	2.298
	ACP3	0.716	1.445
	ACP4	0.786	1.900
	ACP5	0.787	1.750
ASCLI40	ASCLI401	0.722	1.756
	ASCLI402	0.875	2.738
	ASCLI403	0.860	2.526
	ASCLI404	0.850	2.610
	ASCLI405	0.811	2.527
CTC	CTC1	0.793	1.958
	CTC2	0.809	2.192
	CTC3	0.822	2.183
	CTC4	0.828	2.412
	CTC5	0.838	2.303
DOC	DOC1	0.724	1.877
	DOC2	0.797	2.599
	DOC3	0.863	3.000
	DOC4	0.881	2.510
	DOC5	0.847	2.193
FCAC	FCAC1	0.744	1.698

Construct	Indicator	Outer Loading	VIF
	FCAC2	0.847	2.438
	FCAC3	0.846	2.863
	FCAC4	0.862	2.809
	FCAC5	0.783	1.825
ILI40	ILI402	0.863	1.650
	ILI403	0.770	1.467
	ILI404	0.827	1.524

Note: ILI401 was excluded due to its low outer loading (0.415). All retained indicators have outer loadings above 0.70 and VIF values ≤ 3.00 .

Table 4. Heterotrait–Monotrait Ratio (HTMT)

Construct	ACP	ASCLI40	CTC	DOC	FCAC	ILI40
ACP	—					
ASCLI40	0.486	—				
CTC	0.260	0.137	—			
DOC	0.077	0.098	0.314	—		
FCAC	0.308	0.117	0.599	0.400	—	
ILI40	0.204	0.135	0.388	0.155	0.225	—

Note: HTMT values were obtained from the final SmartPLS measurement model after removal of ILI401.

Discriminant validity was first assessed using the Heterotrait–Monotrait ratio (HTMT). As reported in Table 4, all HTMT values are well below the conservative threshold of 0.85 (Henseler et al., 2009; Hair et al., 2022), ranging from 0.077 for DOC–ACP to 0.599 for FCAC–CTC. These results indicate satisfactory discriminant validity and suggest that the six latent constructs capture empirically distinct dimensions of the Lean–Industry 4.0 framework.

The Fornell–Larcker criterion (Fornell and Larcker, 1981) provides additional evidence of discriminant validity. As shown in Table 5, the square root of the AVE for each construct, reported on the main diagonal, exceeds its correlations with all other constructs. For example, the highest inter-construct correlation is observed between FCAC and CTC (0.530), which remains below the corresponding square roots of AVE for FCAC (0.818) and CTC (0.818). The Fornell–Larcker results therefore corroborate the HTMT assessment and support satisfactory discriminant validity across the six constructs.

Table 5. Fornell–Larcker Criterion

Construct	ACP	ASCLI40	CTC	DOC	FCAC	ILI40
ACP	0.780					
ASCLI40	0.421	0.826				
CTC	0.225	0.115	0.818			
DOC	-0.058	-0.057	0.298	0.825		
FCAC	0.265	0.101	0.530	0.380	0.818	
ILI40	0.160	0.111	0.322	0.125	0.189	0.821

Note: Diagonal values represent the square root of the AVE for each construct; off-diagonal values represent inter-construct correlations.

Taken together, the assessment of indicator reliability, internal consistency reliability, convergent validity, indicator-level collinearity, and discriminant validity supports the adequacy of the final measurement model. Following the removal of ILI401, the remaining 28 indicators exhibit satisfactory psychometric properties, providing an appropriate basis for evaluating the structural model.

4.3. Structural Model Evaluation

The structural model was evaluated after establishing the reliability and validity of the measurement model. The assessment focused on the explanatory power of the endogenous constructs, structural collinearity, effect sizes, and out-of-sample predictive performance. Accordingly, the evaluation considered the coefficients of determination (R^2 and adjusted R^2), inner variance inflation factors (VIF), f^2 effect sizes, and the PLSpredict procedure.

The coefficient of determination (R^2) was used to assess the proportion of variance explained in each endogenous construct. As shown in Table 6, the final model explains 33.2% of the variance in Technological Complexity and Costs (CTC), 15.7% in Organisational and Cultural Challenges (DOC), 12.3% in Continuous Process Improvement and Production Flexibility (ACP), and 17.7% in Competitive Advantage (ASCLI40). The corresponding adjusted R^2 values are slightly lower, indicating that the explanatory estimates remain stable after accounting for the number of predictors.

Table 6. Explanatory and Predictive Assessment of Endogenous Constructs

Endogenous Construct	R^2	Adjusted R^2	Q^2_{predict}
CTC	0.332	0.326	0.317
DOC	0.157	0.151	0.133
ACP	0.123	0.110	0.063
ASCLI40	0.177	0.174	0.011

Note: Q^2_{predict} values were obtained using the PLSpredict procedure. ILI40 and FCAC are not included because they are exogenous constructs in the final structural model.

The results indicate that the model has its greatest explanatory capacity for CTC ($R^2 = 0.332$), while the explained variance is more modest for DOC, ACP, and ASCLI40. These values should be interpreted in the context of a behavioral and organisational model based on cross-sectional respondent-level data rather than as evidence of high predictive determination.

Structural collinearity was assessed using the inner variance inflation factor (VIF) values for the predictor constructs. Across the final structural model, inner VIF values ranged from 1.000 to 1.515, with the highest values observed for CTC $\rightarrow$ ACP (1.515) and FCAC $\rightarrow$ ACP (1.503). All values remained well below commonly applied critical thresholds, indicating that predictor collinearity does not represent a concern in the structural model. Accordingly, the estimated path coefficients can be interpreted without evidence of problematic multicollinearity among the predictor constructs.

Effect sizes (f^2) were examined to assess the incremental contribution of each predictor construct to the explained variance of its respective endogenous construct. The results indicate substantial variation across structural relationships. The largest effect is observed for FCAC $\rightarrow$ CTC ($f^2 = 0.341$), followed by ACP $\rightarrow$ ASCLI40 ($f^2 = 0.215$). Smaller effects are observed for FCAC $\rightarrow$ DOC (0.081), ILI40 $\rightarrow$ CTC (0.076), FCAC $\rightarrow$ ACP (0.052), and DOC $\rightarrow$ ACP (0.040), whereas the remaining structural relationships exhibit comparatively limited incremental explanatory contributions.

The individual f^2 values are reported together with the corresponding path coefficients and bootstrap significance tests in Table 7. For completeness, Table 7 also reports the standardized path coefficients and corresponding bootstrapping statistics for the five hypothesized relationships and four complementary structural associations.

Table 7. Structural Path Coefficients, Effect Sizes, and Bootstrapping Results

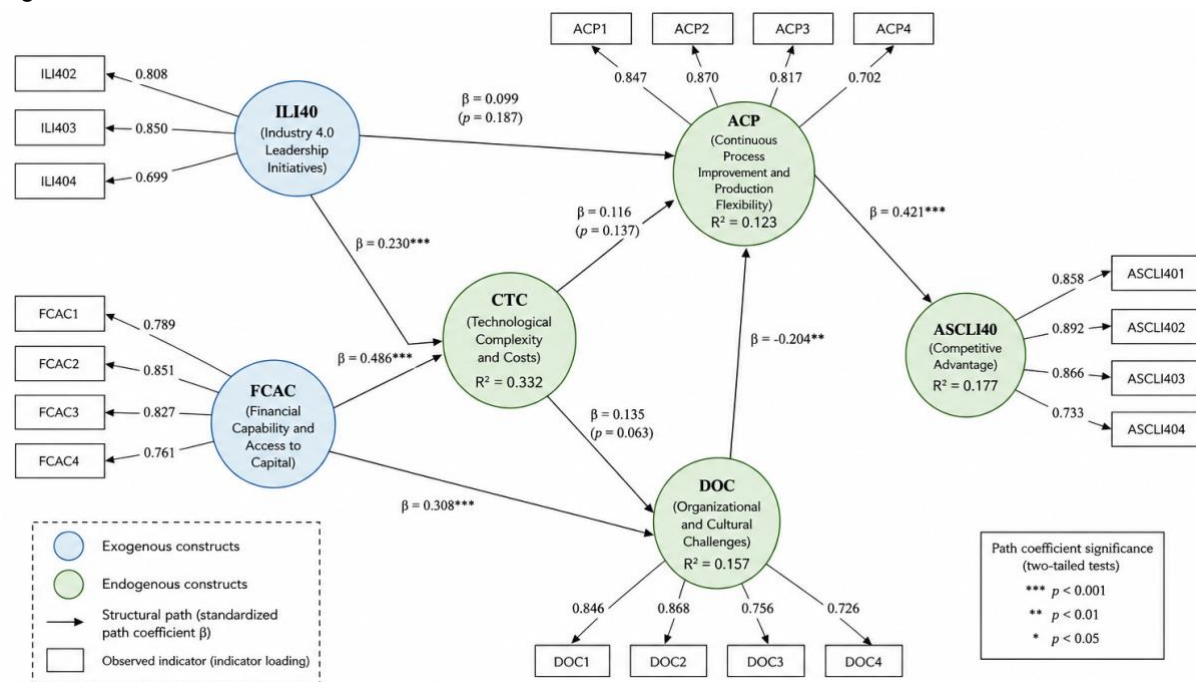
Relationship	β	SD	t-value	p-value	95% CI	f^2	Assessment
H1: ILI40 $\rightarrow$ ACP	0.099	0.075	1.318	0.187	[-0.044, 0.251]	0.010	Not supported
H2: DOC $\rightarrow$ ACP	-0.204	0.066	3.089	0.002	[-0.330, -0.071]	0.040	Supported
H3: FCAC $\rightarrow$ ACP	0.262	0.079	3.334	<0.001	[0.108, 0.415]	0.052	Supported
H4: CTC $\rightarrow$ ACP	0.116	0.078	1.487	0.137	[-0.036, 0.271]	0.010	Not supported
H5: ACP $\rightarrow$ ASCLI40	0.421	0.078	5.411	<0.001	[0.273, 0.574]	0.215	Supported
E1: ILI40 $\rightarrow$ CTC	0.230	0.048	4.778	<0.001	[0.135, 0.323]	0.076	Significant
E2: CTC $\rightarrow$ DOC	0.135	0.073	1.862	0.063	[-0.011, 0.278]	0.016	Not significant
E3: FCAC $\rightarrow$ CTC	0.486	0.045	10.833	<0.001	[0.397, 0.573]	0.341	Significant
E4: FCAC $\rightarrow$ DOC	0.308	0.072	4.269	<0.001	[0.169, 0.450]	0.081	Significant

Note: β = standardized path coefficient; SD = bootstrap standard deviation; CI = percentile bootstrap 95% confidence interval; f^2 = effect size. H1–H5 represent the theoretically specified hypotheses, whereas E1–E4 represent complementary structural associations. Statistical significance was assessed at $p < 0.05$.

Source: Authors' calculations based on the final SmartPLS 4 PLS-SEM algorithm and bootstrapping results.

Figure 2 summarizes the estimated final PLS-SEM structural model, displaying the standardized path coefficients for the five hypothesized relationships and four complementary structural associations, together with the R^2 values of the endogenous constructs. Out-of-sample predictive performance was assessed using the PLSpredict procedure in SmartPLS 4, rather than blindfolding-based Stone–Geisser Q^2 . At the construct level, all endogenous constructs exhibit positive Q^2 predict values: CTC = 0.317, DOC = 0.133, ACP = 0.063, and ASCLI40 = 0.011. These positive values indicate that the PLS-SEM model provides predictive information beyond a naïve benchmark for each endogenous construct, although the magnitude of predictive relevance differs considerably across outcomes. At the indicator level, PLSpredict results generally support the predictive performance of the model. The PLS-SEM root mean squared error (RMSE) is lower than that of the linear-model benchmark for 19 of the 20 endogenous indicators. The only exception is CTC5, for which the PLS-SEM RMSE is marginally higher than the corresponding linear-model value. Similarly, most PLS-SEM mean absolute errors (MAE) are lower than their linear-model counterparts. These results suggest that the model exhibits useful out-of-sample predictive performance, although predictive strength is not uniform across all constructs and indicators.

Figure 2. Final PLS-SEM Structural Model Results



Note: Values on the arrows are standardized path coefficients (β). R^2 values are shown inside the endogenous constructs.

Source: Authors' calculations based on the final SmartPLS 4 PLS-SEM algorithm results.

Overall, the structural-model assessment indicates the absence of problematic predictor collinearity and shows differentiated explanatory and predictive performance across the endogenous constructs. The strongest explanatory and predictive results are observed for CTC, whereas ACP and ASCLI40 display comparatively more modest explained variance and predictive relevance. The implications of the supported, unsupported, and complementary structural relationships are examined in the following sections.

5. Hypothesis Testing and Complementary Structural Relationships

The statistical significance of the structural relationships was assessed using the bootstrapping results reported in Table 7. The analysis distinguishes between the five theoretically specified hypotheses (H1–H5) and the four complementary structural associations (E1–E4) included in the final model. Hypotheses were considered supported when the estimated path coefficient was statistically significant at the 5% level and its direction was consistent with the theoretically specified relationship. Because E1–E4 were not formulated as a priori hypotheses, their statistical significance is interpreted as complementary evidence rather than confirmatory hypothesis support.

For H1, the relationship between Lean–Industry 4.0 Integration (ILI40) and Continuous Process Improvement and Production Flexibility (ACP) is positive but not statistically significant ($\beta = 0.099$, $t = 1.318$, $p = 0.187$, 95% CI $[-0.044, 0.251]$). The confidence interval includes zero and the effect size is very small ($f^2 = 0.010$). Consequently, H1 is not supported. The results therefore do not provide sufficient evidence that Lean–Industry 4.0 integration is directly associated with higher continuous process improvement and production flexibility in the sampled firms.

For H2, Organisational and Cultural Challenges (DOC) are significantly and negatively associated with Continuous Process Improvement and Production Flexibility (ACP) ($\beta = -0.204$, $t = 3.089$, $p = 0.002$, 95% CI $[-0.330, -0.071]$). The direction of the relationship is consistent with the hypothesis formulated in Section 2.2, while the effect size is relatively small ($f^2 = 0.040$). Accordingly, H2 is supported, indicating that greater organisational and cultural challenges are associated with weaker continuous-improvement and production-flexibility outcomes.

For H3, Training and Change Management (FCAC) show a positive and statistically significant relationship with Continuous Process Improvement and Production Flexibility (ACP) ($\beta = 0.262$, $t = 3.334$, $p < 0.001$, 95% CI $[0.108, 0.415]$). The effect size is small ($f^2 = 0.052$), but the direction and statistical significance of the relationship are consistent with the theoretical expectation. Therefore, H3 is supported, providing evidence that training and change-management capabilities are positively associated with continuous-improvement dynamics in Lean–Industry 4.0 environments.

For H4, the relationship between Technological Complexity and Costs (CTC) and Continuous Process Improvement and Production Flexibility (ACP) is positive and statistically non-significant ($\beta = 0.116$, $t = 1.487$, $p = 0.137$, 95% CI $[-0.036, 0.271]$, $f^2 = 0.010$). In addition to the absence of statistical significance, the estimated coefficient does not exhibit the negative direction proposed in H4. Consequently, H4 is not supported. The results do not provide empirical evidence that technological complexity and implementation costs directly constrain continuous process improvement in the sampled firms.

For H5, Continuous Process Improvement and Production Flexibility (ACP) are positively and significantly associated with Competitive Advantage (ASCLI40) ($\beta = 0.421$, $t = 5.411$, $p < 0.001$, 95% CI $[0.273, 0.574]$). This relationship also exhibits the largest effect size among the five confirmatory paths ($f^2 = 0.215$). Accordingly, H5 is supported, indicating that stronger continuous-improvement and production-flexibility capabilities are associated with greater competitive advantage.

Additional indirect-effect results provide further context for the role of Competitive Advantage (ASCLI40) as the final endogenous outcome of the model. The bootstrapping results indicate a significant positive indirect association between Training and Change Management and Competitive Advantage through Continuous Process Improvement and Production Flexibility (FCAC $\rightarrow$ ACP $\rightarrow$ ASCLI40; $\beta = 0.110$, $p = 0.006$), as well as a significant negative indirect association between Organisational and Cultural Challenges and Competitive Advantage through ACP (DOC $\rightarrow$ ACP $\rightarrow$ ASCLI40; $\beta = -0.086$, $p = 0.011$). These effects are reported as supplementary structural evidence and should not be interpreted as formally hypothesized mediation effects, since mediation was not specified a priori in the confirmatory model.

Complementary Structural Relationships

The complementary structural analysis provides additional evidence concerning the relationships among technological integration, implementation complexity, training and change-management capabilities, and organisational conditions. These paths are interpreted separately from H1–H5 because they were not formulated as a priori hypotheses.

Lean–Industry 4.0 Integration is positively and significantly associated with Technological Complexity and Costs (E1: ILI40 $\rightarrow$ CTC; $\beta = 0.230$, $t = 4.778$, $p < 0.001$, 95% CI [0.135, 0.323], $f^2 = 0.076$). This result suggests that greater integration of Lean practices with Industry 4.0 technologies is associated with greater perceived technological complexity and implementation demands.

By contrast, the relationship between Technological Complexity and Costs and Organisational and Cultural Challenges (E2: CTC $\rightarrow$ DOC) is positive but does not reach the 5% significance threshold ($\beta = 0.135$, $t = 1.862$, $p = 0.063$, 95% CI [−0.011, 0.278], $f^2 = 0.016$). Therefore, the final model does not provide sufficient statistical evidence for this complementary association.

Training and Change Management show the strongest complementary structural relationship with Technological Complexity and Costs (E3: FCAC $\rightarrow$ CTC; $\beta = 0.486$, $t = 10.833$, $p < 0.001$, 95% CI [0.397, 0.573], $f^2 = 0.341$). The positive coefficient should be interpreted according to the operationalization of the CTC construct and does not, by itself, demonstrate that training reduces technological complexity. Rather, it indicates a substantial positive association between the two constructs in the estimated model.

Finally, Training and Change Management are positively and significantly associated with Organisational and Cultural Challenges (E4: FCAC $\rightarrow$ DOC; $\beta = 0.308$, $t = 4.269$, $p < 0.001$, 95% CI [0.169, 0.450], $f^2 = 0.081$). As with E3, the positive sign should be interpreted in accordance with the coding and substantive meaning of the DOC indicators and should not automatically be characterized as evidence that training reduces organisational barriers.

Overall, three of the five theoretically specified hypotheses are supported (H2, H3, and H5), whereas H1 and H4 are not supported. Among the four complementary structural associations, E1, E3, and E4 are statistically significant, whereas E2 is not. These findings indicate that the empirical structure of Lean–Industry 4.0 integration is differentiated: direct technological integration alone is not significantly associated with continuous process improvement, whereas organisational conditions, training and change-management capabilities, and continuous-improvement processes display statistically meaningful relationships within the final model.

6. Discussion of Research Results

6.1. Interpretation of Empirical Findings

The empirical findings provide a differentiated picture of Lean–Industry 4.0 integration in the Moroccan automotive sector. Rather than supporting a simple technology-driven performance mechanism, the results indicate that the relationships among technological integration, organisational conditions, human capabilities, continuous improvement, and competitive advantage are more complex. Of the five theoretically specified hypotheses, H2, H3, and H5 are supported, whereas H1 and H4 are not supported. The complementary structural analysis further identifies significant associations for E1, E3, and E4, while E2 does not reach the conventional 5% significance threshold.

The non-significant relationship between Lean–Industry 4.0 Integration (ILI40) and Continuous Process Improvement and Production Flexibility (ACP) does not support H1 ($\beta = 0.099$, $p = 0.187$). This result indicates that, within the sampled firms, greater integration of Lean practices and Industry 4.0 technologies is not by itself associated with significantly higher continuous-improvement and production-flexibility outcomes.

The finding therefore cautions against interpreting digital technology adoption as an automatic source of operational improvement. Instead, technological capabilities may require complementary organisational routines, workforce competencies, and managerial capabilities before measurable performance improvements emerge. This interpretation is consistent with research conceptualizing Lean–Industry 4.0 integration as a socio-technical process involving technology, Lean practices, and people rather than as an exclusively technological transformation (Frank et al., 2024).

The H1 result does not necessarily contradict previous evidence concerning the complementarity between Lean and Industry 4.0. Frank et al. (2025) show that Lean practices and Industry 4.0 technologies may affect operational and worker-related outcomes through distinct and potentially competing mechanisms. The absence of a significant direct ILI40 → ACP relationship in the present study may therefore indicate that the operational benefits associated with technological integration depend on the organisational context in which technologies are introduced and used. However, because mediation was not specified and formally tested as part of the confirmatory model, the present findings should not be interpreted as evidence of a specific mediated mechanism.

H2 is supported, as Organisational and Cultural Challenges (DOC) are negatively and significantly associated with Continuous Process Improvement and Production Flexibility (ACP) ($\beta = -0.204$, $p = 0.002$). This finding indicates that organisational resistance, insufficient internal capabilities, coordination difficulties, and cultural barriers are associated with weaker continuous-improvement dynamics. The result reinforces the view that Lean–Industry 4.0 transformation cannot be understood solely in terms of technological availability. Organisational routines, culture, workforce engagement, and adaptive capabilities remain important conditions for translating technological resources into operational outcomes. This interpretation is consistent with research emphasizing organisational readiness and human capabilities in Industry 4.0 implementation (Sony and Naik, 2020), the role of organisational culture (Wiese et al., 2024), and the dynamic capabilities required to integrate Lean and Industry 4.0 effectively (Komkowski et al., 2025).

H3 is also supported. Training and Change Management (FCAC) are positively and significantly associated with Continuous Process Improvement and Production Flexibility (ACP) ($\beta = 0.262$, $p < 0.001$). This result highlights the relevance of human-capital development, organisational learning, employee involvement, managerial commitment, and structured change-management practices for continuous improvement in digitally transforming manufacturing environments. Technological investment may therefore be more effectively accompanied by stronger improvement capabilities when firms simultaneously develop the skills and organisational processes required to use and adapt new technologies. The finding is consistent with the socio-technical interpretation of Lean–Industry 4.0 proposed by Frank et al. (2024) and with the dynamic-capabilities perspective advanced by Komkowski et al. (2025). It is also consistent with recent evidence linking the digitalization of human-resource practices to labour-productivity improvements (Vader et al., 2025).

By contrast, H4 is not supported. Technological Complexity and Costs (CTC) are not significantly associated with Continuous Process Improvement and Production Flexibility (ACP) ($\beta = 0.116$, $p = 0.137$), and the estimated coefficient is positive rather than negative as hypothesized. The findings therefore do not provide evidence that technological complexity and implementation costs directly constrain continuous-improvement outcomes in the sampled firms. This does not imply that implementation complexity is irrelevant. Instead, its relationship

with operational improvement may depend on organisational conditions, implementation maturity, available capabilities, or other mechanisms not directly captured by the hypothesized CTC → ACP relationship. Given the cross-sectional design, these possibilities should be treated as directions for further research rather than inferred from the present model.

The strongest confirmatory relationship concerns H5, which is supported. Continuous Process Improvement and Production Flexibility (ACP) are positively and significantly associated with Competitive Advantage (ASCLI40) ($\beta = 0.421$, $p < 0.001$), with an effect size of $f^2 = 0.215$. This finding identifies continuous improvement and production flexibility as an important operational mechanism associated with competitive outcomes in the final model. Improvements in responsiveness, process efficiency, waste reduction, production flexibility, and the capacity to adjust operations to changing requirements may therefore strengthen firms' competitive positioning. This result is consistent with the operational logic of Lean Management and with research emphasizing the role of integrated Lean–Industry 4.0 approaches in operational improvement and more responsive production systems (Utiyama et al., 2025; Saraswat et al., 2025).

The additional indirect-effect results further reinforce the central role of ACP in the structural framework. They indicate that Training and Change Management and Organisational and Cultural Challenges are indirectly associated with Competitive Advantage through their respective positive and negative relationships with continuous improvement and production flexibility. This pattern positions ACP as an important operational link between organisational conditions and the final competitive outcome. However, these are interpreted as supplementary structural evidence rather than as formally tested mediation effects and, importantly, do not establish an indirect effect of ILI40 itself on Competitive Advantage.

The complementary structural relationships provide additional insight into the empirical configuration of the model. Lean–Industry 4.0 Integration is positively and significantly associated with Technological Complexity and Costs (E1: ILI40 → CTC; $\beta = 0.230$, $p < 0.001$). This result suggests that greater technological integration may coexist with greater implementation complexity and resource requirements. Such an association is plausible in industrial environments where increased connectivity, automation, system integration, and data infrastructure introduce additional technical and investment demands.

The relationship between Technological Complexity and Costs and Organisational and Cultural Challenges (E2: CTC → DOC) is positive but does not reach statistical significance at the 5% level ($\beta = 0.135$, $p = 0.063$). Consequently, the results do not provide sufficient evidence to conclude that higher technological complexity is systematically associated with greater organisational and cultural challenges. Although the p -value is relatively close to 0.05, this relationship should not be characterized as partially supported under the significance criterion adopted in this study.

Training and Change Management show the strongest complementary association with Technological Complexity and Costs (E3: FCAC → CTC; $\beta = 0.486$, $p < 0.001$, $f^2 = 0.341$). FCAC is also positively and significantly associated with Organisational and Cultural Challenges (E4: FCAC → DOC; $\beta = 0.308$, $p < 0.001$). These positive coefficients require careful interpretation. They do not provide evidence that training and change management reduce technological complexity or organisational barriers. Rather, firms reporting stronger training and change-management capabilities also report higher levels on the CTC and DOC constructs. One possible interpretation is that firms facing more demanding technological and organisational transformations mobilize greater training and change-management efforts.

Alternatively, firms with more developed transformation programmes may simultaneously exhibit greater awareness of implementation complexity and organisational challenges. Because the data are cross-sectional, the direction of these underlying mechanisms cannot be established from the present analysis.

Taken together, the findings indicate that the empirical structure of Lean–Industry 4.0 integration is not characterized by a simple linear progression from technology adoption to improved performance. The direct ILI40 → ACP relationship is not statistically significant, whereas organisational challenges are negatively associated with ACP, training and change-management capabilities are positively associated with ACP, and ACP in turn shows a substantial positive association with competitive advantage. The results therefore emphasize the importance of organisational and human capabilities alongside technological integration, while also showing that the relationships among these dimensions are more nuanced than a straightforward barrier-reduction mechanism. Overall, the evidence supports a socio-technical interpretation of Lean–Industry 4.0 transformation in which technological, organisational, and human dimensions interact within the broader process of continuous improvement and competitive development.

6.2. Economic, Regional, and Policy Implications

At the firm level, the findings suggest that the economic returns associated with Lean–Industry 4.0 depend not only on technological integration but also on the organisational and human capabilities through which production processes are continuously improved. The significant positive relationship between Training and Change Management (FCAC) and Continuous Process Improvement and Production Flexibility (ACP), together with the positive association between ACP and Competitive Advantage (ASCLI40), provides a firm-level basis for interpreting Lean–Industry 4.0 in terms of productivity and resource efficiency. When workforce capabilities, organisational learning, and continuous-improvement practices enable firms to achieve shorter cycle times, lower non-quality costs, reduced downtime, more stable production flows, and more effective use of industrial assets, these efficiency gains may contribute to higher labour productivity and more efficient utilization of installed capital.

When sustained over time and diffused across firms and suppliers, such improvements may also contribute to total factor productivity (TFP) by enabling firms to generate greater output through improved organisation, knowledge, coordination, process design, and data utilization rather than through proportional increases in labour or capital inputs. Importantly, the present study does not directly estimate labour productivity, capital productivity, TFP, or regional economic growth. These broader economic effects should therefore be interpreted as potential implications of the firm-level structural relationships rather than as directly estimated macroeconomic effects.

For Morocco, these mechanisms are particularly relevant to the automotive sector because of its integration into international production networks and global value chains. Stronger continuous-improvement capabilities may enhance the ability of domestic suppliers to meet international requirements concerning quality, cost, delivery reliability, flexibility, and technological standards. Over time, such capability development may support upgrading toward higher-value-added activities and facilitate learning and knowledge spillovers within regional automotive ecosystems. This interpretation is consistent with the OECD's (2024) emphasis on productivity upgrading, skills development, and deeper domestic participation in

global value chains as important elements of Morocco's economic convergence and industrial development.

These productivity and capability mechanisms may also influence the attractiveness of Moroccan automotive locations to foreign direct investment (FDI). Multinational investors consider not only labour costs and physical infrastructure but also supplier quality, workforce skills, technological readiness, production reliability, and the capacity of local firms to absorb increasingly sophisticated production standards. An industrial ecosystem characterized by capable suppliers, skilled employees, continuous-improvement routines, and effective digital integration may therefore strengthen location attractiveness and support reinvestment or the allocation of higher-value activities. Recent evidence concerning the Moroccan automotive industry similarly identifies infrastructure, institutional conditions, and qualified labour as relevant factors in FDI localization (Griguer and Ait Lhassan, 2024).

However, the developmental benefits of FDI depend on the strength of local linkages. Without supplier development, skills transfer, local sourcing, and domestic capability building, foreign investment may generate limited productivity spillovers. Policy should therefore seek to strengthen the mechanisms through which FDI contributes to knowledge diffusion, innovation, workforce upgrading, and the integration of domestic suppliers into higher-value segments of automotive value chains. Innovation capabilities may reinforce these processes by enabling firms to adapt technologies, reorganise production, and respond more effectively to international market requirements, consistent with evidence linking endogenous innovation to firms' market and export performance (Carboni and Medda, 2024).

These economic implications also provide a basis for more targeted industrial-policy interventions. Most importantly, the non-significant direct relationship between Lean–Industry 4.0 Integration and Continuous Process Improvement (H1) suggests that support for industrial digitalization should not assume that technology acquisition alone will automatically generate operational improvements. Public support for Industry 4.0 adoption should therefore combine technological upgrading with workforce development, organisational learning, change-management capabilities, and continuous-improvement systems.

In this context, the Ministry of Industry and Trade, the Moroccan Investment and Export Development Agency (AMDIE), and relevant vocational-training institutions could develop or reinforce co-financed Industry 4.0 upgrading schemes for automotive firms and SMEs. Support for equipment, software, automation, and digital integration could be accompanied by workforce-training plans, managerial commitment, organisational-readiness assessments, and measurable operational objectives. Eligible projects could combine digital-readiness diagnostics, Lean–digital transformation roadmaps, data and cybersecurity readiness, and targeted training in Manufacturing Execution Systems (MES), the Internet of Things (IoT), industrial data analytics, predictive maintenance, automation, and digitally enabled Lean practices.

Shared demonstration centres, regional training platforms, and train-the-trainer schemes could further reduce the costs of experimentation and capability development for SMEs that may be unable to finance sophisticated digital infrastructure independently. Particular attention should be given to supervisors and middle managers because the results indicate that training and change-management capabilities are positively associated with continuous-improvement outcomes. At the same time, the significant negative relationship between Organisational and Cultural Challenges (DOC) and ACP suggests that organisational readiness, internal

coordination, employee involvement, and managerial commitment should be assessed alongside technical feasibility and investment costs.

Supplier development should constitute another important policy dimension. Investment incentives and industrial-development programmes could encourage multinational automotive firms to cooperate with local suppliers through mentoring, employee training, technology transfer, common digital standards, quality-development programmes, and joint improvement initiatives. Such measures may increase the likelihood that FDI contributes to domestic capability formation and productivity spillovers rather than remaining concentrated within foreign-owned production facilities.

Finally, the effectiveness of public support should be evaluated through measurable economic and operational outcomes rather than technology-adoption counts alone. Relevant indicators could include output per worker, defect rates, overall equipment effectiveness (OEE), downtime, capital utilization, production lead times, export intensity, local sourcing, employee skill development, and supplier upgrading. Linking industrial-support programmes to observable capability and productivity outcomes would provide a stronger basis for assessing whether Industry 4.0 investments generate sustainable firm-level and regional economic value.

Conclusion

This study examined the integration of Lean Management and Industry 4.0 technologies in the Moroccan automotive sector using PLS-SEM and survey data from 263 managers and professionals involved in Lean and/or Industry 4.0 implementation. By jointly considering technological integration, organisational and cultural challenges, training and change management, technological complexity and costs, continuous process improvement and production flexibility, and competitive advantage, the study provides empirical evidence on the organisational conditions associated with Lean–Industry 4.0 transformation.

The findings show that Lean–Industry 4.0 integration should not be understood as a simple technology-to-performance mechanism. The direct relationship between Lean–Industry 4.0 Integration (ILI40) and Continuous Process Improvement and Production Flexibility (ACP) is not statistically significant, and H1 is therefore not supported. Similarly, the hypothesized negative relationship between Technological Complexity and Costs (CTC) and ACP is not supported. These results indicate that technological integration and implementation complexity alone do not explain continuous-improvement outcomes in the sampled firms.

By contrast, the organisational and human dimensions of the model provide more substantial empirical evidence. Organisational and Cultural Challenges (DOC) are negatively associated with Continuous Process Improvement and Production Flexibility, supporting H2, whereas Training and Change Management (FCAC) are positively associated with ACP, supporting H3. Continuous Process Improvement and Production Flexibility are, in turn, positively associated with Competitive Advantage (ASCLI40), providing support for H5 and representing the strongest confirmatory relationship in the model. Taken together, these findings highlight the importance of continuous-improvement capabilities and the organisational conditions within which industrial digitalization takes place.

Additional indirect-effect results reinforce the role of continuous improvement as an important operational link between organisational conditions and the final competitive outcome, without constituting formally tested mediation effects.

The complementary structural relationships provide further insight into this transformation process. Greater Lean–Industry 4.0 integration is positively associated with Technological Complexity and Costs, while Training and Change Management show significant positive associations with both Technological Complexity and Costs and Organisational and Cultural Challenges. These findings should not be interpreted as evidence that training increases implementation barriers or, conversely, that it necessarily reduces them. Rather, they suggest that training, change management, technological complexity, and organisational challenges coexist within more intensive transformation processes. Given the cross-sectional research design, the direction of these underlying mechanisms cannot be established from the present analysis.

From an economic perspective, the findings suggest that the potential productivity benefits of Lean–Industry 4.0 are likely to depend on firms' ability to combine technological investment with human-capital development, organisational learning, and continuous-improvement capabilities. Improvements in process efficiency, production flexibility, workforce capabilities, and the utilization of industrial assets may contribute to higher labour productivity and more efficient use of installed capital. If such capabilities diffuse across suppliers and production networks, they may also support industrial upgrading, stronger participation in global value chains, and the development of regional automotive ecosystems.

For Morocco, these firm-level mechanisms have potential implications for industrial and investment policy. Industry 4.0 support programmes should therefore extend beyond incentives for technology acquisition and incorporate workforce training, organisational-readiness assessment, supplier development, managerial capability building, and measurable productivity objectives. Strengthening the capabilities of domestic automotive suppliers may also increase their capacity to absorb knowledge and technology from multinational firms and enhance the potential for local sourcing, productivity spillovers, and higher-value-added participation in global automotive value chains.

These broader economic implications nevertheless require cautious interpretation. The present study does not directly estimate labour productivity, total factor productivity (TFP), foreign direct investment (FDI), export performance, or regional economic growth. Accordingly, these outcomes represent economic implications derived from the observed firm-level relationships rather than effects directly demonstrated by the PLS-SEM model.

The study is also subject to several limitations. First, the use of a non-probability purposive and snowball sample limits the statistical generalizability of the findings beyond the surveyed respondents. Second, because the total number of individuals who ultimately received the questionnaire was not recorded, a reliable response rate cannot be calculated. Third, the number of distinct companies represented in the sample and the number of respondents per company were not formally recorded, preventing an assessment of potential within-company clustering. Fourth, the cross-sectional and self-reported nature of data does not permit causal inference or analysis of how Lean–Industry 4.0 capabilities evolve over time.

Future research should therefore validate the model using larger and more systematically constructed samples, preferably recording firm identifiers or adopting firm-level sampling designs that allow organisational clustering to be assessed. Longitudinal research would be particularly valuable for examining whether technological integration, training, organisational adaptation, and continuous-improvement capabilities develop sequentially over time. Future studies could also formally test mediation and moderation mechanisms rather than inferring indirect relationships from structural associations.

Further research should additionally combine perceptual survey measures with objective firm-level indicators such as output per worker, defect rates, overall equipment effectiveness, downtime, capital utilization, investment intensity, exports, wages, and productivity. Linking firm-level evidence with regional data on value added, employment, FDI, and supplier networks would allow the broader productivity and regional-development implications proposed in this study to be tested directly.

Overall, the study contributes to the Lean–Industry 4.0 literature by showing that industrial digital transformation in the Moroccan automotive sector is better understood as a socio-technical and capability-dependent process than as an automatic consequence of technology adoption. The findings place continuous improvement, organisational conditions, and human-capital development at the centre of the relationship between industrial digitalization and competitive performance. This perspective also provides a relevant foundation for future research on more human-centred, adaptive, and resilient manufacturing systems associated with the transition toward Industry 5.0.

CRediT Authorship Contribution Statement

Salem, N.: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Al Meriouh, Y.: Supervision, Validation, Methodological guidance, Writing – review & editing.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The statistical outputs supporting the measurement-model, structural-model, bootstrapping, indirect-effect, and predictive-performance analyses are available in a supplementary workbook accompanying the online version of this article. The respondent-level dataset is not publicly deposited because public data sharing was not documented as part of the participant consent process. Anonymized data may be available from the corresponding author upon reasonable request, subject to applicable confidentiality and ethical considerations.

Ethical Approval Statement

The study involved a voluntary questionnaire survey of professional respondents and did not collect sensitive personal or medical information. Participation was voluntary, and informed consent was obtained from all respondents. The authors report that, under the institutional requirements applicable to this study, formal ethical approval was not required.

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Appendix A. Survey Instrument

A.1. Respondent and Organizational Characteristics

Q1. Gender

- Male
- Female

Q2. Company's field of activity within the automotive sector

- Wiring
- Plastics
- Textiles
- Mechanics
- Electrical
- Other

Q3. Number of employees

- Fewer than 100
- 100–499
- 500–999
- 1,000 or more

A.2. Measurement Items

Respondents were asked to indicate their level of agreement with each statement using a five-point Likert scale:

1 = Strongly disagree | 2 = Disagree | 3 = Neutral | 4 = Agree | 5 = Strongly agree

Construct 1. Lean–Industry 4.0 Integration (ILI40)

Code	Measurement item
ILI401	Combining Lean tools (e.g., 5S, Kaizen, and TPM) with Industry 4.0 technologies improves process performance.
ILI402	Industry 4.0 technologies facilitate the traceability and control of Lean operations through MES and IoT systems.
ILI403	Industry 4.0 technologies improve the management of Lean production flows, including Just-in-Time and Kanban systems.
ILI404	Automation and connectivity in Lean production systems improve process efficiency and reduce waste (Muda).

Construct 2. Organizational and Cultural Challenges (DOC)

Code	Measurement item
DOC1	Resistance to change slows the adoption of Industry 4.0 technologies.
DOC2	A lack of internal skills represents a barrier to Industry 4.0 integration.
DOC3	Organizational challenges complicate the integration of Lean and Industry 4.0, particularly in the application of SMED and Poka-Yoke.

DOC4	Insufficient collaboration between departments hinders digital transformation and the optimization of Value Stream Mapping (VSM) flows.
DOC5	Organizational culture influences the speed of new-technology adoption and the implementation of Hoshin Kanri.

Construct 3. Training and Change Management (FCAC)

Code	Measurement item
FCAC1	Continuous training is essential for the effective adoption of Industry 4.0 technologies and the effective use of Lean tools.
FCAC2	Investment in training and change management supports continuous improvement through practices such as Kaizen.
FCAC3	Employee involvement in digital transformation increases acceptance of technological change and facilitates the application of Lean practices such as 5S and Gemba Walk.
FCAC4	Leadership and management commitment are key success factors in the digitalization of Lean Management.
FCAC5	A structured change-management program facilitates the Lean–Industry 4.0 transition and reduces organisational resistance.

Construct 4. Technological Complexity and Implementation Costs (CTC)

Code	Measurement item
CTC1	The cost of Industry 4.0 technologies represents a significant barrier to their adoption.
CTC2	Lean tools need to be adapted (e.g., digital Kaizen and electronic Kanban) to ensure their effective integration with Industry 4.0 technologies.
CTC3	The technical complexity of Industry 4.0 technologies slows their deployment in Lean production processes.
CTC4	Uncertainty regarding the short-term return on investment in Industry 4.0 technologies can constrain their implementation and the digital monitoring of Lean performance indicators such as OEE and lead time.
CTC5	Limited access to specialized suppliers and technical expertise slows the implementation of Industry 4.0 solutions and the optimization of Lean Six Sigma processes.

Construct 5. Continuous Improvement and Production Flexibility (ACP)

Code	Measurement item
ACP1	The integration of Lean Management and Industry 4.0 increases production flexibility.
ACP2	Automation reduces cycle times and improves operational responsiveness within an SMED approach.

ACP3	The digitalization of Lean processes facilitates continuous improvement through tools such as digital Andon and Kaizen.
ACP4	The use of real-time data improves decision-making and the monitoring of Lean performance indicators.
ACP5	The robotization of repetitive tasks enables labour to be reallocated to higher value-added activities within a Lean production environment.

Construct 6. Competitive Advantage (ASCLI40)

Code	Measurement item
ASCLI401	Integrating Lean Management and Industry 4.0 strengthens my company's competitiveness by reducing non-quality costs.
ASCLI402	Companies that effectively adopt Industry 4.0 technologies can outperform competitors through improved operational efficiency.
ASCLI403	Lean–Industry 4.0 synergy improves customer satisfaction and overall performance by optimizing Just-in-Time production.
ASCLI404	The use of Industry 4.0 technologies promotes innovation within the company and improves Takt Time management.
ASCLI405	A well-defined strategy for integrating Industry 4.0 strengthens market positioning and organizational agility.