Journal of Mechanical Engineering and Manufacturing
https://www.sciltp.com/journals/jmem

Article

Business Productivity and the Adoption of Lean and Industry 4.0 Tools: A Regional Study

André Guimarães [1,2,*], Rosivalda Pereira [3], Marisa Pereira [4] and Maria Teresa Pereira [4]

[1] CISE–Electromechatronic Systems Research Centre, Department of Electromechanical Engineering, University of Beira Interior, 6201-001 Covilhã, Portugal
[2] CISeD–Research Centre for Digital Services, Polytechnic of Viseu, Campus Politécnico Santa Maria, Av. Cor. José Maria Vale de Andrade, 3504-510 Viseu, Portugal
[3] UFMA–Sistema Integrado de Bibliotecas, Universidade Federal do Maranhão, Av. dos Portugueses, 1966-Vila Bacanga, São Luís, MA 65080-805, Brasil
[4] LAETA-INEGI, ISEP, Polytechnic of Porto, Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal
* Correspondence: andre.m.guimaraes@ubi.pt or aguimaraes@estgv.ipv.pt

How To Cite: Guimarães, A.; Pereira, R.; Pereira, M.; et al. Business Productivity and the Adoption of Lean and Industry 4.0 Tools: A Regional Study. *Journal of Mechanical Engineering and Manufacturing* **2025**, *1*(1), 6. https://doi.org/10.53941/jmem.2025.100006.

Received: 30 May 2025
Revised: 16 June 2025
Accepted: 2 July 2025
Published: 8 July 2025

Abstract: This study investigates the relationship between the adoption levels of Lean and Industry 4.0 (I4.0) tools and business productivity among 140 industrial companies in the Central Region of Portugal. Lean and I4.0 adoption indices were constructed and categorized into tertiles. Productivity data were retrieved from the SABI database. Statistical analysis using non-parametric methods revealed a marginally significant association between Lean tool adoption and productivity (Kruskal-Wallis $H(2) = 5.30$, $p = 0.071$), indicating a positive trend. In contrast, a statistically significant relationship was found for Industry 4.0 adoption ($H(2) = 8.39$, $p = 0.015$, Dunn's $p = 0.039$), with companies with low adoption levels underperforming those with medium and high levels. No significant productivity differences were observed by firm size ($p = 0.154$). These findings highlight the relevance of Lean and I4.0 tools as productivity drivers, regardless of company size, and underscore the importance of promoting structured digital and operational transformation strategies in low digital maturity regions.

Keywords: lean tools; industry 4.0 tools; business productivity; regional study; Portugal

1. Introduction

The Fourth Industrial Revolution, known as Industry 4.0 (I4.0), began in 2011 at the Hannover Technology Fair in Germany [1]. Its main objective is to enhance companies' competitiveness and efficiency by integrating the physical and digital worlds, called Cyber-Physical Systems (CPS) [2]. Studies by Rüßmann et al. [3] indicate that Germany, as a pioneer in this transformation, foresees a significant economic impact, estimating a productivity increase between 5% and 8%, a 1% rise in Gross Domestic Product (GDP), and up to 6% more jobs in the industrial sector [2].

In recent decades, the industrial landscape has been transformed by the adoption of continuous improvement approaches, such as Lean Manufacturing, and the integration of emerging digital technologies associated with Industry 4.0. These approaches aim to enhance business productivity through process optimization, waste reduction, and improved operational flexibility. In Portugal, particularly in the central region, the capacity of companies to adopt and integrate these tools varies significantly depending on their size, sector of activity, and level of digitalization, raising important questions about the determinants of regional productivity. Within this context of digital transformation, Small and Medium-sized Enterprises (SMEs) play a key role, given their substantial contribution to national economic growth [4]. Many of these companies incorporate Industry 4.0

concepts through the Lean philosophy [5–7], with evidence suggesting a positive relationship between this integration and business performance [8]. To achieve high levels of industrial productivity, these organisations must develop structures that promote operational efficiency, combining technological adoption with the enhancement of the human factor [9].

Integrating Lean tools with Six Sigma methodologies, known as Lean Six Sigma (LSS), has proven promising when combined with Industry 4.0 technologies. This combination fosters significant improvements in productivity and operational efficiency [10]. One example of this integration is the study by Duc et al. [11], which applied the DMAIC methodology (Define; Measure; Analyze; Improve; Control) to improve process quality, increase productivity, reduce waste, shorten delivery times, meet customer needs, and enhance business profitability.

Authors such as Kamble et al. [12] emphasise that Lean is a mediating factor in adopting Industry 4.0, and organisations should integrate both paradigms to achieve greater organisational intelligence and productive efficiency. This view is reinforced by the growing importance attributed to the joint adoption of Lean tools and Industry 4.0 technologies as a strategy to address the challenges of digital transformation.

This research aims to address a gap in literature by analyzing the intersection between the levels of adoption of Lean tools and the levels of adoption of Industry 4.0 technologies, with a particular focus on their impact on business productivity. In addition to offering an updated theoretical perspective, the study presents empirical evidence from a moderately industrialised region, enhancing the understanding of this integration in contexts comparable to Central Portugal. This contribution is especially relevant for companies aiming to optimise production processes and overcome challenges typically faced in medium-sized industrial regions.

Section 1 presents the relevance, and Section 2 presents a literature review. Section 3 describes the research methodology, Section 4 analyzes and discusses the results, and Section 5 provides a discussion and critical analysis. Finally, Section 6 presents the conclusions, practical implications, and future directions of the research.

2. Literature Review

The digitalisation of companies, driven by the Industry 4.0 paradigm, is a key factor in enhancing productivity and business competitiveness. According to Karuppiah et al. [13], technologies such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), and Big Data contribute not only to greater efficiency and agility but also to more sustainable manufacturing processes. However, this digital transformation presents significant challenges for small and medium-sized enterprises (SMEs), often facing limited resources, technological capabilities, and organisational structure [13].

The integrated application of Lean tools alongside Industry 4.0 technologies has emerged as a promising strategy to increase productivity in industrial companies. According to Rohani and Zahraee [10], combining these approaches shows greater improvement potential than implementing them in isolation. Studies such as Duc et al. [11] demonstrate the effectiveness of applying the DMAIC model focused on defining, measuring, analysing, improving, and controlling in enhancing the quality, eliminating waste, and reducing delivery times, resulting in increased productivity and profitability.

Integrating Lean tools throughout various operational phases has promoted operational efficiency and continuous improvement [14,15]. When adopted in industrial settings, this collaborative model contributes to customer satisfaction and enhanced organisational competitiveness [11].

Combining Lean tools with digital technologies has proven to be an effective way to improve organisational performance. According to Emir et al. [16], more innovative companies with a higher capacity to adopt digital tools tend to be more productive. Thus, the joint adoption of tools focused on waste elimination and continuous improvement, together with Industry 4.0 technologies, can generate significant operational gains in physical and digital processes.

Technological tools are key in transforming organisations in today's digital industrial landscape. These technologies boost productivity and help companies achieve long-term strategic goals [8]. To fully harness this potential, it is essential to integrate human capabilities with both Industry 4.0 and Lean tools [9], while fostering new business models oriented towards technological innovation.

Small and medium-sized enterprises (SMEs) represent a vital segment of the global economy and play a significant role in national economic development [4]. Nevertheless, these organisations face greater challenges in adapting to the digital revolution, making it crucial to establish organisational structures that support industrial productivity. Research shows that SMEs performance is influenced by the Industry 4.0 technologies they adopt [17] and the practical implementation of Lean tools, which help reduce failures and waste [4].

Studies such as Cirillo et al. [18] highlight that digitalisation has a greater positive impact on the productivity of already more technologically mature and adaptable SMEs. This supports the idea that successful technology adoption also depends on sound organisational practices, including data-driven planning and performance control systems [19].

Company size is another critical factor in adopting Lean and Industry 4.0 tools. Larger companies generally have more financial, technological, and human resources, making it easier to implement change and integrate innovative practices into their daily operations [20].

Digital transformation in SMEs requires a cautious approach. According to Rossi et al. [21], to address the challenges associated with digitalisation, it is recommended that some Lean tools be digitally adapted beforehand to ensure a more effective and integrated adoption of Industry 4.0 technologies.

Lean thinking, initially developed by Toyota after World War II, remains widely recognised as a core philosophy for improving organisational performance. This approach promotes systematic waste elimination, efficiency gains, and value creation [22]. Training employees to use Lean tools has helped strengthen their skills and productivity [23]. When combined with the innovations brought by Industry 4.0, such training better equips workers to handle complex tasks, increases adaptability [24], and fosters safer, more sustainable working environments [25]. Among the types of waste identified in the Lean philosophy, human talent waste is highlighted by Ohno (2019) as the eighth waste to be eliminated.

The relationship between Lean and Industry 4.0 has attracted growing attention in the literature. Several authors point out that these approaches reinforce each other and can act as mutual enablers [11,26,27]. By reducing waste and standardising processes, Lean lays the foundation for effective Industry 4.0 (I4.0) implementation, while I4.0 enhances Lean practices through digitalisation and integration of information systems [27,28].

Within this context, Lean 4.0 emerges, resulting from the fusion of Lean practices and 4.0 digital tools. This approach enables real-time defect detection and automation of Lean processes [21], offering new opportunities to optimise production systems.

Despite progress in this area, most studies have focused mainly on the technological aspects of Lean 4.0 integration, overlooking more practical and organisational perspectives [29]. Furthermore, there is a scarcity of empirical studies that examine this integration from a regional perspective, particularly regarding its direct impact on business productivity.

Some initiatives linked to Industry 4.0 and digital transformation have gained visibility in Portugal, yet many companies face significant challenges [30,31]. Portuguese firms report barriers to implementing Industry 4.0, particularly the need for investment and strategic change management [32,33]. Nevertheless, overcoming these technological challenges is essential to unlock opportunities to improve production processes and use resources more efficiently [34].

The literature thus lacks a more comprehensive systematisation and in-depth studies on the intersection of Lean, LSS, and Industry 4.0, especially within the context of regions with specific industrial realities [21,35]. This research aims to address part of that gap.

The relationship between the level of adoption of Lean and Industry 4.0 tools and business productivity remains scarce in the existing literature and current research that considers regional and organizational specificities in specific contexts, namely in the Portuguese case. This research addresses some of the questions raised by responding to the hypotheses formulated.

3. Research Methodology

3.1. Research Methods

The Lean Tools Adoption Index was similarly classified into tertiles (low, medium, and high) to reflect the level of implementation of Lean practices within each company. The Lean tools considered in this analysis include: 5S, VSM—Value Stream Mapping, JIT—Just in Time, Kanban, Kaizen, Visual Management, FMEA—Failure Mode and Effects Analysis, PDCA—Plan, Do, Check, Act, Standard Work/Standardisation, TPM—Total Productive Maintenance, Cause-and-Effect Diagram, SMED—Single Minute Exchange of Dies, Six Sigma, Heijunka, Jidoka, Poka-Yoke, BSC—Balanced Scorecard, the 7 Wastes/Muda, OEE—Overall Equipment Effectiveness, DMAIC—Define, Measure, Analyse, Improve, Control, TPS—Toyota Production System, TQM—Total Quality Management, and WIP—Work in Progress.

The Lean Index was constructed using the arithmetic mean of the individual tool scores. This method is commonly used in the literature to simplify the interpretation of aggregated indicators [36]. The index is defined by the following expression:

$$I = \text{Lean Tools Adoption Index} = \frac{1}{23}\sum_{1=1}^{23} Pi$$

where:

Pi be the score of Lean tools *i*, where *i* = 1, 2, 3, ..., 23.

This result classified the ranking into tertiles: low, moderate, and high.

The Industry 4.0 Tools Adoption Index was calculated using a weighted sum approach, implemented in Python. This method allows for intuitive interpretation while maintaining computational simplicity, as supported in the literature [37].

To facilitate interpretation, the technologies were categorised into two groups. Basic Technologies include radio frequency identification (RFID), real-time location systems, sensors, mobile devices, and automation. Enabling Technologies, typically associated with Industry 4.0, comprise cloud technologies (as scalable IT infrastructures), Big Data, M2M (Machine-to-Machine) communications, virtual and/or augmented reality, artificial intelligence, and embedded IT systems.

Each technology was assigned a weight of 1 for Basic Technologies and 2 for Enabling Technologies, and a composite score was calculated for each company. The resulting index was then classified into tertiles, corresponding to low, medium, and high levels of adoption.

The following general equation defines the weighted index:

$$I = \text{I4.0 Tools Adoption Index} = \sum_{i=1}^{n} x_i \,.\, w_i$$

where:

- I = Final weighted index for each observation.
- x_i = Presence (1) or absence (0) of technology *i* in the observation.
- w_i = Weight assigned to technology *i* (1 for basic technologies or 2 for enabling technologies).
- n = Total number of technologies considered.

This result classified the ranking into tertiles: low, medium, and high.

3.2. Data Collection and Sample

Primary data were collected through two structured questionnaires, designed explicitly for this study. These instruments allowed a detailed quantitative analysis of the tools implemented by each company, covering Lean and Industry 4.0 (I4.0) practices. Based on the responses, an index was constructed to assess the level of adoption of Lean and I4.0 tools in industrial companies of different sizes located in a region of central Portugal. A total of 140 companies actively participated in this research. In addition to primary data, secondary data on business productivity was obtained from the SABI (Bureau Van Dijk) database [38], providing relevant operational performance indicators for each company.

Specifically, business productivity was measured as Gross Value Added (GVA) per employee, based on the following equation:

$$\text{Productivity} = \frac{\text{Gross Value Added (GVA)}}{\text{Number ofemployees}}$$

In this context, Gross Value Added (GVA) represents the economic value generated by a company after subtracting the costs of goods and services used in the production process. By relating GVA to the number of employees, this indicator reflects the average economic value generated per worker, making it a key measure of efficiency, competitiveness, and business performance.

The descriptive statistics of the sample are summarized in Tables 1 and 2.

Table 1. Descriptive statistics of business productivity in the sample.

Char.	Obs.	Mean	Std. Dev.	Min.	Max.	P25	P50	P75
Business Productivity € thousands	140	39.532	33.514	5.229	227.624	21.509	31.540	43.544

Table 2. Distribution of Lean and I4.0 tool adoption levels and company size.

Characteristic	Region n = 140
Adoption level of Lean Tools	
Low	47 (33.6%)
Medium	46 (32.9%)
High	47 (33.6%)
Adoption level of I4.0 Tools	
Low	56 (40.0%)
Medium	39 (27.9%)
High	45 (32.1%)
Size	
Large	85 (60.7%)
Medium	41 (29.3%)
Small	14 (10.0%)

3.3. Research Questions

Considering the gaps identified in this research, the following research question was addressed:

RQ: What is the relationship between the levels of adoption of Lean tools and Industry 4.0 and the business productivity in a region in central Portugal?

A conceptual model was developed to answer the research question (RQ) and validate the formulated hypotheses (H1, H2 and H3), as illustrated in Figure 1. This model provides a clear and logical structure that makes it easier to understand the impact of the level of adoption of Lean and Industry 4.0 tools on business productivity.

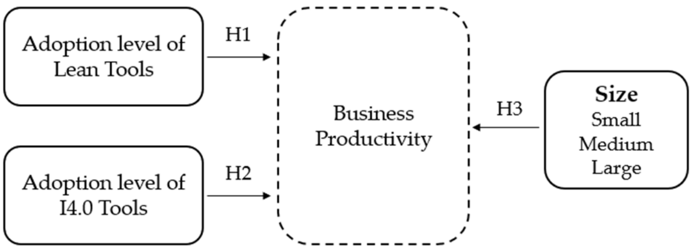

Figure 1. Conceptual model.

The research gap is focused on the lack of studies that comprehensively analyze the impact of the different levels of adoption of Lean and Industry 4.0 tools on the business productivity of Portuguese companies of various sizes. In this sense, industrial companies in one of the regions of central Portugal were analyzed in detail. The opportunity to explore this theme and validate formulated research hypotheses stands out.

H1: *The level of adoption of Lean tools is positively correlated with business productivity.*

H2: *The level of adoption of Industry 4.0 tools positively correlates with business productivity.*

H3: *Company size has a positive impact on business productivity.*

4. Results

4.1. Relationship between the Level of Adoption of Lean Tools and Business Productivity

Hypothesis H1 was tested using the Kruskal-Wallis test, as the variable "Business Productivity" did not follow a normal distribution, according to the Shapiro-Wilk test applied through Python software [39]. For this reason, a non-parametric test suitable for comparing independent groups was employed.

The results in Table 3 revealed a marginally significant difference between the groups defined by the level of Lean tool adoption ($H = 5.30$; $p = 0.071$). Although the p-value does not reach the conventional threshold for statistical significance ($p < 0.05$), an observable positive trend indicates an association between the degree of Lean implementation and the productivity levels reported by industrial firms in the Central Region of Portugal.

Table 3. Relationship between business productivity and adopting Lean tools.

Hypothesis	Variables Analyzed	Statistical Test	Statistic	*p*-Value	Significance
H1	Lean Tools Adoption × Business Productivity	Kruskal-Wallis H(2)	5.3	0.071	Marginal

This pattern is particularly relevant considering the sample's composition, which includes companies of various sizes, many of which are small and medium-sized enterprises (SMEs) with limited capacity for full Lean adoption. Nevertheless, the results suggest that higher levels of adoption are associated with progressive gains in productivity, indicating that implementing Lean practices may contribute to operational efficiency and continuous improvement, even in resource-constrained contexts. Accordingly, the findings support the importance of promoting policies and initiatives that encourage the structured adoption of Lean tools within the regional business landscape.

Figure 2 shows the distribution of business productivity according to the levels of Lean tool adoption: low, moderate, and high. A rising trend in median productivity values is observed as the adoption level increases. Companies with high adoption present a higher median productivity than the others, suggesting a possible positive association between the systematic application of Lean practices and business performance.

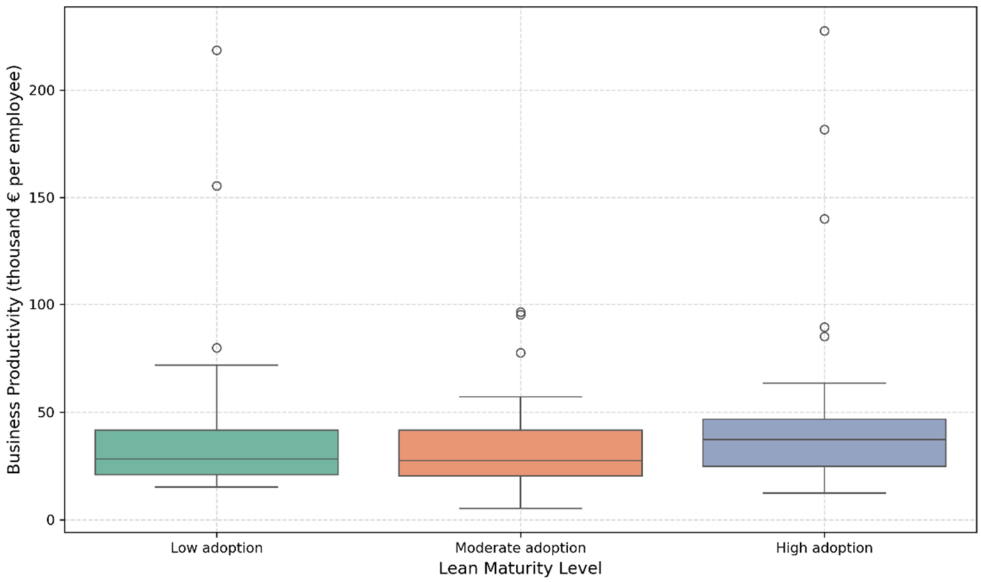

Figure 2. Business productivity by level of Lean tool adoption (low, moderate, and high). The box plot shows the median, variability, and outliers.

Although the difference between groups is not statistically significant at the 5% level ($p = 0.071$), the visualization reinforces the trend identified in the statistical analysis. It suggests that broader adoption of Lean tools may have a practical impact on the productivity of companies in the Central Region of Portugal. Outliers in all groups also indicate performance heterogeneity, possibly explained by other organisational factors such as operational maturity, industry sector, or company size.

4.2. Relationship between the Level of Adoption of Industry 4.0 Tools and Business Productivity

To test Hypothesis H2, the Kruskal-Wallis test was applied to examine whether firm productivity differed significantly between firms with different levels of technology adoption (low, medium, high). The Kruskal-Wallis test was chosen because the independent variable is an ordinal categorical variable with three groups, and the dependent variable (productivity) did not follow a normal distribution.

As shown in Table 4, the test result was statistically significant ($H(2) = 8.39$, $p = 0.015$), indicating the presence of relevant differences in median productivity between the levels of technological adoption.

To explore which specific groups differed from each other, Dunn's post-hoc test with Holm's correction for multiple comparisons was conducted, as illustrated in Table 5. The results revealed that the low adoption group differed significantly from the medium and high adoption groups ($p = 0.039$). At the same time, no significant difference was found between the medium and high groups ($p = 0.986$).

Table 4. Relationship between business productivity and adopting I4.0 tools.

Hypothesis	Variables Analyzed	Statistical Test	Statistic	*p*-Value	Significance
H2	I4.0 Tools Adoption × Business Productivity	Kruskal-Wallis H(2)	8.39	0.015	Significant

Table 5. Matrix of adjusted p-values (Holm correction) for pairwise group comparisons using Dunn's test.

	High	Medium	Low
High	1	0.986	0.039
Medium	0.986	1	0.039
Low	0.039	0.039	1

These findings confirm a positive association between the level of Industry 4.0 adoption and business productivity. Notably, the main distinction is between low-tech companies and those with at least partially implemented Industry 4.0 technologies. This suggests that even moderate adoption of digital tools may be associated with performance gains, while companies with minimal adoption may be at a distinct disadvantage.

Figure 3 shows the distribution of business productivity for companies with low, medium, and high levels of Industry 4.0 tool adoption. The boxplot highlights an apparent increase in median productivity from the Low to the Medium group. Although there is no significant difference between the Medium and High groups, both perform better than the Low group, which has the lowest median and least variability.

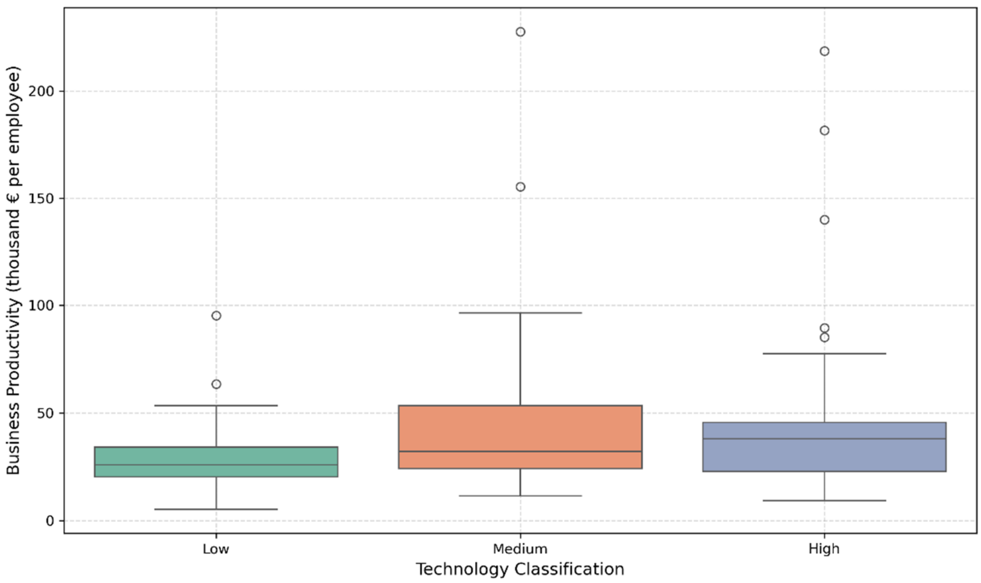

Figure 3. Business productivity by level of I4.0 tool adoption (low, medium, and high). The box plot shows the median, variability, and outliers.

These results support the statistical analysis and suggest that even a moderate technology adoption can improve productivity. The outliers in all groups reflect differences in how effectively companies use these tools, which may depend on factors like workforce skills or business sector.

The findings highlight the need to improve access to technology and support in the Central Region of Portugal, where many SMEs have low digital maturity. Actions such as training, digital maturity assessments, and targeted funding can help increase productivity and reduce disparities across companies.

4.3. Relationship between Company Size and Business Productivity

To test Hypothesis H3, the Kruskal-Wallis test was applied to compare business productivity between different sizes of companies (small, medium, and large), as illustrated in Table 6. This non-parametric test was justified due to the non-normal distribution of the productivity variable and the presence of three independent groups.

Table 6. Relationship between business productivity and company size.

Hypothesis	Variables Analyzed	Statistical Test	Statistic	*p*-Value	Significance
H3	Company Size × Business Productivity	Kruskal-Wallis H(2)	3.7397	0.1541	not significant

The test result was not statistically significant (H(2) = 3.74; $p = 0.154$), indicating insufficient evidence to reject the null hypothesis. In other words, firm size does not significantly affect business productivity in this sample.

This result suggests that productivity levels are not necessarily determined by company size in the context of the companies located in the Central Region of Portugal. Several explanations can be considered. First, smaller companies can adopt efficient practices or niche strategies to achieve productivity levels comparable to those of larger companies. On the other hand, larger companies may face structural complexities or operational inefficiencies that offset the advantages typically associated with scale.

Figure 4 supports this conclusion by showing the distribution of business productivity across the three size categories. Although large companies exhibit a slightly higher median productivity, the variability is also greater, and the differences between groups are not statistically significant. Small and medium-sized enterprises (SMEs) show overlapping ranges and similar distributions, despite outliers being present in all three groups.

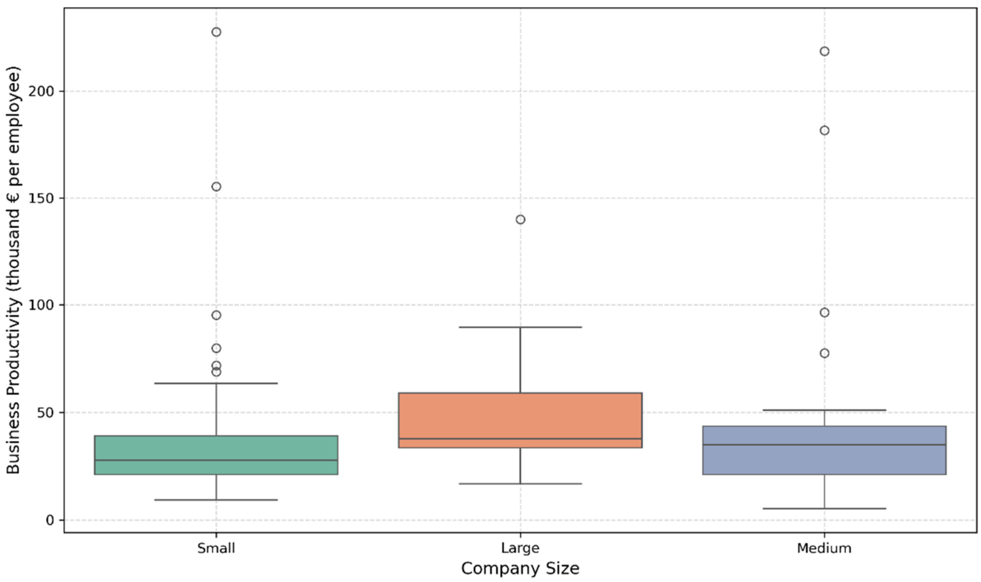

Figure 4. Distribution of business productivity by company size (small, medium, and large). The boxplot displays median values, variability, and outliers.

These findings are consistent with previous studies suggesting that digital tools and organizational practices may play a more decisive role in performance than structural factors such as size alone. The results of H1 and H2 indicated positive associations between productivity and adopting Lean and Industry 4.0 tools, reinforcing the idea that technological and process-related capabilities can outweigh size as drivers of productivity.

In practical terms, these findings highlight the need for policy support and productivity improvement programs to include companies of all sizes, ensuring that micro, small, medium, and large enterprises can access the tools and strategies they need to boost their performance.

5. Discussion

The present study reinforces the evidence that Industry 4.0 technologies have a significant and more immediate impact on business productivity, while Lean tools show a positive, albeit more gradual, effect. This distinction supports findings in the literature suggesting that digitalisation tends to yield faster returns in technologically mature SMEs [16,18]. Moreover, the observed relationship confirms that even moderate adoption of Industry 4.0 tools can lead to meaningful productivity gains, highlighting the strategic value of structured digital transformation [8,13].

Regarding the role of company size, the results challenge traditional assumptions. No significant differences in productivity were found across different size categories, suggesting that structural scale alone does not guarantee higher performance. As supported by Kuong Rodríguez & Arana Barbier [20], organisational practices, leadership, and effective tool implementation may be more decisive than firm size in shaping productivity outcomes. This is particularly relevant in Portuguese, where many large firms still face internal inefficiencies and operational rigidity. At the same time, some small and medium-sized enterprises (SMEs) adopt agile structures and niche strategies that promote efficiency.

Additionally, the low digital maturity level of the region, as noted by Guimarães et al. [31], may contribute to levelling the playing field between companies of different sizes. The advantages typically associated with scale can be diluted in areas with underdeveloped innovation ecosystems and limited access to advanced technologies. Limited human capital specialisation, insufficient strategic planning, or delayed organisational change in larger firms may reduce their expected productivity gains. At the same time, smaller firms, though resource-constrained, may compensate with faster decision-making, adaptability, and targeted use of digital and Lean tools [4,21].

These findings highlight the need to reconsider firm size as a reliable predictor of productivity, especially in transitional economic contexts. Therefore, policies and support mechanisms should prioritise capability development across all firm sizes, fostering environments where Lean and Industry 4.0 tools are accessible and implementable regardless of scale. Future research could explore these dynamics further through qualitative insights or longitudinal studies that track firm trajectories over time.

6. Conclusions

This research explored the relationship between the levels of adoption of Lean and Industry 4.0 (I4.0) tools and Business Productivity in industrial companies in the Central Region of Portugal. A quantitative methodological approach was used, combining primary data from structured questionnaires with secondary productivity data from the SABI database. Three hypotheses were tested, focusing on the impact of adopting the Lean tool (H1) and adopting the I4.0 tool (H2), as well as company size (H3), on business productivity.

Although company size did not statistically affect productivity in this study, this result may be influenced by unobserved sectoral or capital intensity factors. This limitation has been acknowledged, and future research should explore this relationship more robustly by including non-linear size variables and industry-level controls.

The results indicate a marginally significant association between adopting the Lean tool and business productivity, suggesting that companies that adopt Lean practices more intensively tend to achieve greater productivity. However, the effect does not reach conventional statistical significance. In contrast, the adoption of Industry 4.0 tools demonstrated a statistically significant impact, with companies in the low adoption group performed significantly worse than those with moderate or high adoption levels. These results reinforce the value of digital transformation strategies and structured operational improvements to increase productivity. On the other hand, company size did not significantly influence productivity, indicating that organizational practices and technological capabilities can overcome structural factors such as company size.

These results underscore the importance of Lean and Industry 4.0 tools in driving productivity, even for SMEs in regions with low digital maturity. They also highlight the need for targeted support policies, including training, digital readiness assessments, and financial incentives to encourage wider adoption of these tools, thereby promoting greater competitiveness and performance across the industrial fabric.

Future research could adopt longitudinal approaches to monitor productivity evolution over time, conduct sector-specific analyses to capture industry-specific dynamics, and apply qualitative methods to explore barriers and enablers from managerial and operational perspectives. Integrating digital maturity models could provide a more detailed view of organizational readiness, while expanding the study to other Portuguese regions or international contexts would allow for comparison and broader generalization. Such developments would increase understanding of how Lean and Industry 4.0 tools influence business performance and support more effective industrial competitiveness and sustainability strategies.

Additionally, the result for firm size should be interpreted with caution. Firm size alone may not reflect structural differences between companies, such as industry type or capital intensity. Due to data limitations, we could not include sectoral or capital-related variables in this study. This limitation is now acknowledged. Future research should consider adding size-squared terms and sector-specific controls to improve the robustness of the analysis.

Author Contributions

Conceptualisation: A.G., R.P., M.P. and M.T.P.; methodology: A.G., R.P., M.P. and M.T.P.; validation: A.G., R.P., M.P. and M.T.P.; formal analysis: A.G., R.P. and M.T.P.; investigation: A.G.; data curation: A.G., R.P., M.P. and M.T.P.; writing original draft preparation: A.G.; writing review and editing: A.G., R.P., M.P. and M.T.P.;

visualisation: A.G., R.P., M.P. and M.T.P.; supervision: R.P. and M.T.P.; project administration: A.G.; funding acquisition: A.G. All authors have read and agreed to the published version of the manuscript.

Funding

This research was not funded.

Data Availability Statement

No new data was created.

Acknowledgments

This research was supported by the Portuguese Foundation for Science and Technology (FCT) under Projects UIDB/50022/2020, UIDB/04131/2020, UIDP/04131/2020, UIDB/05583/2020, and UI/BD/154507/2022. The authors would also like to thank Associate Laboratory for Energy, Transports and Aerospace (LAETA-INEGI), CISeD–Research Centre for Digital Services, Polytechnic of Viseu, CISE–Electromechatronic Systems Research Centre, University of Beira Interior (UBI), and the Shift2Future consortium.

Conflicts of Interest

The authors declare that they have no competing interests.

References

1. Kagermann, H.; Lukas, W.D.; Wahlster, W. Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution. *VDI Nachrichten* **2011**, *13*, 2–3.
2. Gu, J.C.; Ling, Z.H.; Zhu, X.; et al. Dually interactive matching network for personalized response selection in retrieval-based chatbots. *arXiv* **2019**, arXiv:1908.05859.
3. Rüßmann, M.; Lorenz, M.; Gerbert, P.; et al. *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*; Boston Consulting Group: Boston, MA, USA, 2015.
4. Qureshi, K.M.; Mewada, B.G.; Alghamdi, S.Y.; et al. Accomplishing sustainability in manufacturing system for small and medium-sized enterprises (SMEs) through lean implementation. *Sustainability* **2022**, *14*, 9732.
5. Di Bona, G.; Duraccio, V.; Silvestri, A.; et al. Validation and application of a safety allocation technique (integrated hazard method) to an aerospace prototype. In Proceedings of the IASTED International Conference on Modelling, Identification, and Control (MIC), Innsbruck, Austria, 17–19 February 2014; pp. 284–290.
6. Falcone, D.; Silvestri, A.; Di Bona, G.; et al. Study and modelling of very flexible lines through simulation. In Proceedings of the 2010 Spring Simulation Multiconference, Orlando, FL, USA, 11–15 April 2010; pp. 1–6.
7. Falcone, D.; Silvestri, A.; Forcina, A.; et al. Modeling and simulation of an assembly line: A new approach for assignment and optimization of activities of operators. In Proceedings of MAS—The International Conference on Modeling and Applied Simulation, Rome, Italy, 12–14 September 2011; pp. 12–14.
8. Gallo, T.; Cagnetti, C.; Silvestri, C.; et al. Industry 4.0 tools in lean production: A systematic literature review. *Procedia Comput. Sci.* **2021**, *180*, 394–403.
9. Lasi, H.; Fettke, P.; Kemper, H.G.; et al. Industry 4.0. *Bus. Inf. Syst. Eng.* **2014**, *6*, 239–242.
10. Rohani, J.M.; Zahraee, S.M. Production line analysis via value stream mapping: A lean manufacturing process of color industry. *Procedia Manuf.* **2015**, *2*, 6–10.
11. Duc, M.L.; Hlavaty, L.; Bilik, P.; et al. Enhancing manufacturing excellence with lean six sigma and zero defects based on Industry 4.0. *Adv. Prod. Eng. Manag.* **2023**, *18*, 32.
12. Kamble, S.; Gunasekaran, A.; Dhone, N.C. Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. *Int. J. Prod. Res.* **2020**, *58*, 1319–1337.
13. Karuppiah, K.; Sankaranarayanan, B.; D'Adamo, I.; et al. Evaluation of key factors for Industry 4.0 technologies adoption in small and medium enterprises (SMEs): An emerging economy context. *J. Asia Bus. Stud.* **2023**, *17*, 347–370.
14. Sarı, T.; Güleş, H.K.; Yiğitol, B. Awareness and readiness of Industry 4.0: The case of Turkish manufacturing industry. *Adv. Prod. Eng. Manag.* **2020**, *15*, 57–68.
15. Kregel, I.; Stemann, D.; Koch, J.; et al. Process mining for six sigma: Utilising digital traces. *Comput. Ind. Eng.* **2021**, *153*, 107083.

16. Emir, O.; Gergin, Z.; Üney-Yüksektepe, F.; et al. A comparative sectoral analysis of Industry 4.0 readiness levels of Turkish SMEs. In Proceedings of the Digital Conversion on the Way to Industry 4.0: Selected Papers from ISPR2020, Online-Turkey, 24–26 September 2020; Springer: Cham, Switzerland, 2021; pp. 251–263.
17. De Giovanni, P.; Cariola, A. Process innovation through Industry 4.0 technologies, lean practices and green supply chains. *Res. Transp. Econ.* **2021**, *90*, 100869.
18. Cirillo, V.; Fanti, L.; Mina, A.; et al. New digital technologies and firm performance in the Italian economy. *Ind. Innov.* **2023**, *30*, 159–188.
19. Mayer, J.H.; Esswein, M.; Göbel, M.; et al. Getting digital technologies right—A forward-looking maturity model for enterprise performance management. In *Lecture Notes in Information Systems and Organisation*, 52th ed.; Springer: Cham, Switzerland, 2022; pp. 79–96.
20. Kuong Rodríguez, J.U.; Arana Barbier, P.J. Impact of human factor management on company productivity: The moderating effect of digitalization. *Cogent Bus. Manag.* **2024**, *11*, 2371064.
21. Rossi, A.H.G.; Marcondes, G.B.; Pontes, J.; et al. Lean tools in the context of Industry 4.0: Literature review, implementation and trends. *Sustainability* **2022**, *14*, 12295.
22. Womack, J.P.; Jones, D.T. Lean thinking banish waste and create wealth in your corporation. *J. Oper. Res. Soc.* **1997**, *48*, 1148.
23. Stanica, S.; Peydro, J. How does the employee cross-training lean tool affect the knowledge transfer in product development processes? *VINE J. Inf. Knowl. Manag. Syst.* **2016**, *46*, 371–385.
24. Saniuk, S.; Caganova, D.; Saniuk, A. Knowledge and skills of industrial employees and managerial staff for the Industry 4.0 implementation. *Mob. Netw. Appl.* **2023**, *28*, 220–230.
25. Pasi, B.N.; Mahajan, S.K.; Rane, S.B. The current sustainability scenario of Industry 4.0 enabling technologies in Indian manufacturing industries. *Int. J. Product. Perform. Manag.* **2020**, *70*, 1017–1048.
26. Mrugalska, B.; Wyrwicka, M.K. Towards lean production in Industry 4.0. *Procedia Eng.* **2017**, *182*, 466–473.
27. Sanders, A.; Elangeswaran, C.; Wulfsberg, J.P. Industry 4.0 implies lean manufacturing: Research activities in Industry 4.0 function as enablers for lean manufacturing. *J. Ind. Eng. Manag.* **2016**, *9*, 811–833.
28. Bittencourt, V.; Saldanha, F.; Alves, A.C.; et al. Contributions of lean thinking principles to foster Industry 4.0 and sustainable development goals. In *Lean Engineering for Global Development*; Springer: Cham, Switzerland, 2019; pp. 129–159.
29. Moraes, A.; Carvalho, A.M.; Sampaio, P. Lean and Industry 4.0: A review of the relationship, its limitations, and the path ahead with Industry 5.0. *Machines* **2023**, *11*, 443.
30. De Jesus, C.; Lima, R. Study of the Portuguese challenges in the context of European Union to identify adaptation strategies for the Industry 4.0. In Proceedings of the International Conference Innovation in Engineering, Kuala Lumpur, Malaysia, 19–20 October 2021; Springer International Publishing: Cham, Switzerland, 2021; pp. 25–35.
31. Guimarães, A.; Reis, P.; Charrua-Santos, F. Industry 4.0—Assessment of digital readiness of manufacturing companies in Portugal. In Proceedings of the 2023 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 18–21 December 2023; pp. 557–561.
32. Pereira, L.; Gonçalves, R.; Costa, R.; et al. Industry 4.0 in Portugal—The state of the art. *Int. J. Internet Manuf. Serv.* **2023**, *9*, 44–70.
33. Guimarães, A.; Reis, P.; Cardoso, A.J.M. Industry 4.0 in Portugal—Economic sectors maturity. In Proceedings of the 2024 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bangkok, Thailand, 15–18 December 2024; pp. 496–500.
34. Rikalovic, A.; Suzić, N.; Bajić, B.; et al. Industry 4.0 implementation challenges and opportunities: A technological perspective. *IEEE Syst. J.* **2022**, *16*, 2797–2810.
35. Yin, Y.; Stecke, K.E.; Li, D. The evolution of production systems from Industry 2.0 through Industry 4.0. *Int. J. Prod. Res.* **2018**, *56*, 848–861.
36. Durán-Sáenz, I.; Verdú-Soriano, J.; González-de la Torre, H.; et al. Psychometric validation of an instrument to assess undergraduate nursing student's knowledge of the aetiology, prevention and treatment of venous leg ulcers. *Nurse Educ. Today* **2024**, *142*, 106340.
37. Gönül, Ö.; Duman, A.C.; Güler, Ö. A comprehensive framework for electric vehicle charging station siting along highways using weighted sum method. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114455.
38. SABI. *Iberian Balance Sheet Analysis System*; Bureau van Dijk: Madrid, Spain, 2022.
39. Elliott, A.C.; Hynan, L.S. A SAS® macro implementation of a multiple comparison post hoc test for a Kruskal–Wallis analysis. *Comput. Methods Programs Biomed.* **2011**, *102*, 75–80.