The effect of Lean 4.0 on the Triple Bottom Line: a European study

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Abstract: Recently, being sustainable has become pivotal for manufacturing firms to be competitive in the market and improve their position towards environmental, social, and economic impact. Recently, researchers highlighted how technological improvements could play a fundamental role in sustaining firms in this direction. On the other hand, others stated that this impact could be even greater if they are integrated with specific managerial practices such as Lean Management. This study aims to clarify this by showing how firms that integrated Lean Management practices and Industry 4.0 ones have improved their sustainable performance. The results showed that the companies implementing both paradigms are more likely to greatly improve sustainable performance, while those with lower levels of both will obtain the opposite result. Thus, we provided empirical evidence of the benefits of integrating Lean Management and Industry 4.0, and we suggest that firms integrate them to improve their sustainable performance.

Keywords: Lean, Industry 4.0, Kaizen, 3BL, Sustainability

1. Introduction

The pressure on companies' market competitiveness has rapidly increased in recent years. Firms that were used to cope with market pressure for improving operational performance, such as delivery time and time to market, are now requested to improve also their sustainable metrics. Thus, firms must explore an increasingly complex scenario to improve operational efficiency while embracing sustainable practices.

From an external perspective, firms' impact on their environmental footprint is gaining momentum, and customers are increasingly asking for companies with little environmental impact. On the other hand, also the dynamics related to social Sustainability are becoming increasingly important, with the idea of a sustainable firm that plays a social role. Lastly, from a more internal perspective, economic Sustainability is fundamental for the firm to generate value and compete in the market. Knowing that many firms are trying to focus more on improving the TBL (Triple Bottom Line), which includes all three dimensions. Managers nowadays prioritize environmental and social changes alongside profit margins and revenue generation, necessitating increased ESG investments.

This change has been registered in all sectors, including the manufacturing one. An increased technological advance has characterized this industry, thanks to the development of the Industry 4.0 paradigm. Some authors pointed out how these technologies can facilitate the achievement of improved TBL performance. Others, instead, stated that it is true if these technologies are fairly driven through appropriate preparation, for instance, with prior implementation of Lean Management practices and a streamlined of existing processes. These authors stated that when doing so, firms are exploiting a synergetic effect between these managerial practices and technologies, helping them to reach an enhanced level of sustainable performance. Nevertheless, there is still unclarity on whether and how this happens.

Thus, this research aims to investigate the effect of the integration between Lean Management Practices and Industry 4.0 Technologies and their impact on companies' Operational and Sustainable Performance, defined as the Triple Bottom Line, considering the Economic, Environmental, and Social perspectives. Through the use of the survey methodology, this research aims to expand the current knowledge base and provide advice for organizations seeking to use Lean Manufacturing and Industry 4.0 Technologies, i.e., Lean Automation or Lean 4.0 (Rossini et al., 2022), to gain a competitive advantage in the market, all while advocating for sustainable approaches. This work focuses on the manufacturing sector, which is vital to the economies of numerous European countries, emphasising the need for moving towards Sustainability.

2. Theoretical Background

2.1 Lean Manufacturing

Lean Manufacturing was born as part of the Toyota Production System (Ohno, 1988), defined as "a set of management principles and techniques geared towards eliminating waste in the manufacturing process and

increasing the flow of activities that, from the customers' perspective, add value to the product" (Kamble, Gunasekaran, & Dhone, 2020). Numerous studies highlight the unique benefits organizations can obtain by implementing Lean methodologies, enabling them to gain a competitive edge and produce positive Performance results. Studies such as Rossini et al. (2019, 2022) and Tortorella et al. (2019) highlight the widespread adoption of Lean in high-performance environments, demonstrating how the paradigm enhances operational efficiencies and drives significant overall performance improvements.

2.2 Industry 4.0

The proliferation of new technologies has created an increasingly interconnected world, leading to the emergence of the fourth industrial revolution, i.e., Industry 4.0 (I4.0). This revolution stands out as an element of change and renewal capable of redesigning production assets, resource management, the value chain, and the competitive dynamics of companies (Buer, Strandhagen, & Chan, 2018). The fundamental characteristics of I4.0 are connection, interaction, and cooperation between different technologies (Tortorella et al., 2022). In the current industrial context, technologies related to Industry 4.0 are playing an increasingly crucial role in optimizing processes, improving efficiency, and enabling greater flexibility, which are key features for operating in today's market (Narula et al., 2021). It has been demonstrated that this especially happens when technologies are integrated into processes (Hofmann & Rüsch, 2017; Tortorella et al., 2022).

2.3 Lean 4.0

The findings from the literature show how Lean and Industry 4.0 have a mutual positive impact on each other, and their synergies offer the greatest potential benefits for organizations. This integration is commonly called "Lean Automation" or "Lean 4.0" (Rossini et al., 2022).

The shared goals of reducing complexity, streamlining processes, and acknowledging the role of employees are central to both Lean Manufacturing and Industry 4.0. The impact of Lean Automation on Organisational Performance is a topic that is frequently pivotal nowadays, and several studies confirm that the implementation of Lean 4.0 leads to a significant increase in performance (Buer et al., 2021; Rossini et al., 2019, 2022; Tortorella, & Fettermann, 2018).

2.4 Impact of Lean 4.0 on Sustainable Performance and Triple Bottom Line

In the context of heightened global concerns about the environment, social responsibility, and economic longevity, Sustainability is a guiding principle for transforming manufacturing firms. The Triple Bottom Line (TBL) is the concept that emphasizes the assessment of performance not only in Economic (e.g., Profit, Turnover, Production Cost) but also in Social (e.g., Working conditions, Workplace safety, Employee health) and Environmental (e.g., Renewal Energy production, Product durability, Industrial Waste) terms (Elkington, 1997). TBL represents a significant shift in the evolution of business practices, recognizing that long-term success goes beyond the generation of profit alone, embracing social responsibility and the conservation of natural resources.

The Sustainability and Lean 4.0 relationship analysis showed relevant but limited findings. On one side, articles such as Kabzhassarova et al. (2021) and Kamble, Gunasekaran, & Dhone (2020) argue that Lean 4.0 strongly and positively correlates with Sustainability and all its sides. This is also confirmed by others, who argue that the impact of Lean 4.0 on Sustainability metrics is positive, but with a sample limited to a small geographical area (Ghaithan et al., 2021) with no clear answers about extensions in other areas.

2.5 Research Gaps

Current research is lacking in analyzing the impact of Lean 4.0 on indicators linked to the Environmental and Social sides of Sustainability, which are relevant for a firm in the long-term perspective (Rossini et al., 2022). Then, the potential of Industry 4.0 Technologies should be investigated when integrated into organizational processes, as it has been demonstrated to lead to greater improvements in performance (Buer, Strandhagen, & Chan, 2018; Rossini et al., 2022). Finally, in recent years, Lean Manufacturing, Industry 4.0, and Sustainability have received extensive attention and exploration in academic literature (Maware & Parsley, 2023). Nevertheless, the synergistic convergence of these topics remains a relatively underdeveloped macro-theme. Therefore, based on the identified gaps, we formulated the following research question:

"How does the integration between Lean Manufacturing and Industry 4.0 Technologies impact Sustainable Performance?"

3. Methodology

The study employs a survey-based methodology (Montgomery, 2013), using a comprehensive questionnaire divided into five key sections: (i) Degree of Implementation of Lean Practices (41 practices), (ii) Level of Adoption of Industry 4.0 Technologies (19 technologies), (iii) Operational Performance Indicators (4 indicators, (iv) Sustainable Performance Indicators (20 indicators), encompassing Economic, Environmental, and Social aspects, and (v) Details about the Respondents and their respective Companies.

This questionnaire was developed by integrating three frameworks proposed by Rossini et al. (2019) and Rossini et al. (2022), as well as by Kamble, Gunasekaran, and Dhone (2020). Within the sections focusing on Operational Performance Indicators, Lean Practices Implementation level, I4.0 Technologies integration adoption level, and Sustainable Performance Indicators, each metric was evaluated using a Likert scale ranging from 1 (significantly worsened/fully disagree/not adopted) to 5 (significantly improved/fully agree/fully adopted). The detailed items are shown in the Annex.

After the development, five experts externally validated the survey to obtain concrete feedback from the field and make fundamental changes to receive more timely and coherent responses to the industry landscape.

3.1 Data collection

The questionnaire was sent to a group of contacts working in companies collaborating with the authors. The 137 final respondents had different roles in a wide variety of sectors. The contacts met the following requirements: i) respondents should be familiar with Lean Management and Industry 4.0 concepts, and ii) respondents should hold key roles within their companies to have an overall view of managing business processes.

3.2 Analysis

The analyses shown in this study have been performed using Python programming language. The following statistical tests have been performed to check biases (Rossini et al., 2019; Rossini et al., 2022; Tortorella et al., 2021). For the non-response bias, differences between early and late respondents were tested based on equality of variances and equality of means (Armstrong & Overton, 1977). As the results were not significant, any non-response bias issue was disregarded. Then, the reliability of each single construct was tested by calculating Cronbach's alpha values (Tortorella et al., 2021), which all turned out higher than 0.6, verifying the reliability of the items. Finally, the correlation test has been done through Spearman's correlation analysis, resulting in all positive significant correlations.

Cluster Analysis has been performed using the Ward (Rencher, 2005) method to divide each set of variable observations into two groups, defining a High-level and a Low-level group (Tortorella et al., 2021). During the analysis, an ANOVA was performed to verify that the means of the two groups were significantly different (Rossini et al., 2019). Particularly, for each variable of interest, we found the following clusters:

- Lean Manufacturing: HL (High Lean Implementers), LL (Low Lean Implementers).
- Industry 4.0: HI4.0 (High I4.0 Technologies Implementers), LI4.0 (Low I4.0 Technologies Implementers).
- Operational Performance: HOP (High Operational Performance Improvement), LOP (Low Operational Performance Improvement).
- Sustainable Performance: HSP (High Sustainable Performance Improvement), LSP (Low Sustainable Performance Improvement).

Chi-square Analysis (Tabachnick, Fidell, & Ullman, 2013) and contingency tables have been created to compare different variables and understand if there was a significant association. The association of the relationship between variables is confirmed by a p-value lower than 0.05, while we computed the standard errors to assess the significance level (Rossini et al., 2019; Tortorella & Fettermann, 2022).

4. Results

Results from the Chi-square Analysis show how high levels of Operational Performance (OP) are significantly associated with high levels of Lean Implementation and Industry 4.0 Implementation ($\chi2 = 43.408$; p-value < 0.01). The same phenomenon appears to exist for Sustainable Performance (SP), where high levels of SP are associated with high levels of Lean and Industry 4.0 Implementation ($\chi2 = 43.909$; p-value < 0.01).

Considering the interplay between Lean Principles and Industry 4.0 Technologies concerning a company's Operational Performance, a high degree of Lean adoption coupled with the limited implementation of Industry 4.0 Technologies is associated with a higher likelihood of achieving superior Operational Performance. Conversely, extensive use of Industry 4.0 Technologies without effective Lean Practices reduces the probability of achieving high Operational Performance. This suggests that a robust Lean implementation exerts a more potent positive influence on achieving heightened Operational Performance (Rossini et al., 2019; Rossini et al., 2022; Tortorella et al., 2019).

Shifting the focus to the link between Lean Automation and a company's Sustainable Performance, a company with High Lean and Low Industry 4.0 characteristics is more likely to achieve High Sustainable Performance. Conversely, a company with High Industry 4.0 but Low Lean attributes is more prone to Low Sustainable Performance. This highlights the greater benefits associated with Lean practices in this context.

Table 1: Chi-square – Operational Performance

Performance	HOP		LOP	
Clusters	**HL**	**LL**	**HL**	**LL**
HI4.0	32***	5	9	9***
LI4.0	9***	20	7	46**
Total	41	25	16	55

Table 2: Chi-square – Sustainable Performance

Performance	HSP		LSP	
Clusters	**HL**	**LL**	**HL**	**LL**
HI4.0	37***	7	4	7***
LI4.0	12***	21	4	45**
Total	49	28	8	52

* Significant at 10% (adj. res. > |1.64|); ** Significant at 5% (adj. res. > |1.96|); Significant at 1% (adj. res. > |2.58|).

5. Discussion and Conclusion

5.1 Discussion and Implications

To summarise the results obtained from the above analyses, it can be affirmed that Lean 4.0 positively influences Operational and Sustainable performance. While both Lean and Industry 4.0 paradigms individually contribute to enhanced performance, their integration leads to even greater improvements due to the synergies they create.

Separating the effects, it is also possible to state that Lean 4.0 impact on a company's Operational Performance is positive, confirming what was already known in the literature. Lean Manufacturing optimizes efficiency by reducing waste and rationalizing production processes, while Industry 4.0 introduces advanced technologies that enable more accurate control and visibility of these processes. In short, the synergy enhances Operational Performance, making companies more efficient, competitive, and able to adapt quickly to market dynamics. Even though that, it was clear how a more significant role is played by Lean, demonstrated by the fact that low-Lean firms can still achieve an increased level of operational performance, even without technology implementation.

To answer the research question is necessary to state that Lean 4.0 also influences a company's Sustainable Performance, positively affecting each side of Sustainability. From the results of this study, it is possible to hypothesize that Lean 4.0 positively impacts a company's Economic Performance by reducing waste, optimizing production processes, and implementing advanced technologies. This results in greater operational efficiency, lower costs, and increased competitiveness in the market. The same hypothesis can be drawn from a social point of view: this integration can improve the working conditions and the working environment. Reducing repetitive tasks through automation and promoting safer production contributes to employee well-being. A better working environment can increase employee satisfaction, enhance corporate reputation, and increase employee engagement. In environmental terms, this combination reduces the company's ecological impact. It is possible to hypothesize that Lean contributes by minimizing resource waste, while Industry 4.0 technologies can promote Sustainability through more efficient energy management and reduced emissions. This environmentally friendly approach is in line with the growing need for Sustainability.

The results clearly show that the combined impact of Lean Management and Industry 4.0 on Sustainability is significant. However, it is equally clear that merely adopting the emerging Industry 4.0 paradigm may not be sufficient to ensure long-term Sustainability. In particular, the advanced technologies of this paradigm need to be embedded into business processes and integrated with structured management theories. At the same time, the synergetic implementation of technologies within the Lean approach can further enhance the effectiveness of both approaches. The strategic integration of robust management theories and technologies provides companies with a powerful lever to address sustainability challenges in a comprehensive and synergetic manner, enabling them to take full advantage of emerging opportunities and move towards more efficient and sustainable business management.

5.2 Conclusion and Limitations

A significant contribution of this study lies in addressing a notable gap in the existing literature. Most of the studies analyzed were focused on the main relationship between Lean 4.0 and Operational Performance. However, only a few tried to focus on the correlation between Lean 4.0 and Sustainability. Furthermore, those who have done it only have analyzed the impacts of Lean 4.0 on specific parts of the Sustainability concept, not including all three dimensions. Research findings can help organizations steer their business strategies by demonstrating how combining Lean and Industry 4.0 initiatives can lead to tangible benefits regarding operational efficiency and social, environmental, and economic responsibility. Consequently, the contribution is dual: theoretical, as it addresses a gap in the existing literature, and practical, as it offers empirical evidence showcasing the favorable impact of Lean 4.0 on Sustainability.

This study is not exempt from limitations. First, the results and discussion are valid considering the high aggregation level use; thus, we encourage more detailed and specific research that unveils how and why Lean 4.0 sets the basis for improved sustainable performance. Second, in terms of the sample, all respondents were European, which restricts the generalisability of the findings. Future research might include a broader range of nations or a specific selection of countries to increase the robustness of the results. A larger dataset would permit more complex statistical approaches, allowing for more robust indications and more informative conclusions.

Further, this analysis gathered data from manufacturers operating in different industries. With larger datasets, it would be interesting to undertake the same research while isolating individual industries or geographical locations in the future, comparing them with each other to spot commonalities and differences. It may be worthwhile to concentrate the research emphasis and explore these dynamics within industrial landscapes dominated by SMEs, such as the European one.

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Annex – Survey

Section 0 - Company Information

Number of employees in your company: Less than 500 / More or equal to 500

Type of ownership of your company: Family-owned / Corporate-owned

Business operating model: B2B (business-to-business) / B2C (business-to-customer) / B2B and B2C

LP implementation time length: ≤ 5 years /> 5 years

Sector:

Position held by the respondent:

Section 1 – Operational Performance

Please indicate the improvement level of the following operational performance indicators observed in your company during the last three years:

Operational Performance	1 (worsened significantly)	5 (improved significantly)
Productivity		
Delivery Service Level		
Safety		
Quality		

Section 2 – Lean Management

Please indicate below the agreement level with the following statements based on your company's status:

Lean Practices	1 (fully disagree)	5 (fully agree)
We are frequently in close contact with our suppliers		
We give our suppliers feedback on quality and delivery performance		
We strive to establish long-term relationships with our suppliers		
Suppliers are directly involved in the new product development process		
Our key suppliers deliver to the plant on a JIT basis		
We have a formal supplier certification program		
Our suppliers are contractually committed to annual cost reductions		
Our key suppliers are located in close proximity to our plants		
We have corporate-level communication on important issues with key suppliers		
We take active steps to reduce the number of suppliers in each category		
Our key suppliers manage our inventory		
We evaluate suppliers on the basis of total cost and not per unit price		
We are frequently in close contact with our customers		
Our customers give us feedback on quality and delivery performance		
Our customers are actively involved in current and future product offerings		
Our customers are directly involved in current and future product offerings		
Our customers frequently share current and future demand information with the marketing department		
Production is pulled by the shipment of finished goods		
Production at stations is pulled by the current demand of the next station		
We use a pull production system		
We use kanban, squares, or containers of signals for production control		
Products are classified into groups with similar processing requirements		
Products are classified into groups with similar routing requirements		
Equipment is grouped to produce a continuous flow of families of products		
Families of products determine our factory layout		
Our employees practice set-ups to reduce the time required		
We are working to lower set-up times in our plant		
We have low set-up times for equipment in our plant		
A large number of equipment/processes on the shop floor are currently under SPC		
Extensive use of statistical techniques to reduce process variance		
Charts showing defect rates are used as tools on the shop floor		
We use fishbone-type diagrams to identify causes of quality problems		
We conduct process capability studies before product launch		
Shop floor employees are key to problem-solving teams		
Shop floor employees drive suggestion programs		
Shop floor employees lead product/process improvement efforts		
Shop floor employees undergo cross-functional training		
We dedicate a portion of every day to planned equipment maintenance-related activities		
We maintain all our equipment regularly		
We maintain excellent records of all equipment maintenance-related activities		
We post equipment maintenance records on the shop floor for active sharing with employees		

Section 3 – Technologies Adoption

Please indicate below the adoption level of the following digital technologies in your company:

Technologies Adoption	1 (not adopted)	5 (fully adopted)
Big Data Analytics for Manufacturing Optimization		
Machines with digital interfaces and sensors for process control (e.g., product and operating conditions identification)		
IoT for remote monitoring and control		
IoT for internal process optimization (e.g., maintenance, quality)		
IoT for external process optimization (e.g., supply chain control, fleet management)		
Cloud manufacturing for remote monitoring		
Cloud Computing for Manufacturing Execution Systems (MES)		
Edge Computing for Real-Time Analytics		
Cyber-Physical Systems for Smart Factories		
Real-time scanning by smartphone or tablet application		
Autonomous Mobile Robots for Material Handling and assembly		
Augmented reality (AR) for assembly and maintenance		
Simulation for predictive maintenance and asset obsolescence		
Simulation for decision-making (e.g., evaluating investments)		
Remote monitoring and control of production through systems (e.g., MES, SCADA)		
Integrated engineering systems (e.g., PLM, BIM) for product development and manufacturing		
Additive Manufacturing for Customized Products		
Blockchain for Supply Chain Management (for improving cybersecurity, transparency, and traceability of production processes)		
Wearable Technology for Worker Safety		

Section 4 – Sustainable Performance

Please indicate the improvement level of the following sustainable performance indicators observed in your company during the last three years:

Sustainable Performance	1 (worsened significantly)	5 (improved significantly)
ECONOMIC SUSTAINABILITY		
Reduced costs of production		
Improved profits		
Reduced product development costs		
Decreased energy costs		
Reduces inventory costs		
Reduced rejection and rework costs		
Decreased raw material purchasing costs		
Decreased waste treatment costs		
SOCIAL SUSTAINABILITY		
Improved working conditions		
Improved workplace safety		
Improved employee health		
Improved labour relations		
Improved morale		

Decreased work pressure
ENVIRONMENTAL SUSTAINABILITY
Reduction of solid waste
Reduction of liquid waste
Reduced gas emissions
Reduced energy waste
The decrease in consumption of hazardous/harmful/toxic materials
Improvement in the firm's environmental situation