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Integrating Lean Manufacturing with Industry 4.0: The Impact on Indian MSMEs

Abstract: - This research delves into the integration of Lean Manufacturing principles with Industry 4.0 technologies, exploring the emergence of "Lean 4.0" within the distinct operational context of Indian Micro, Small & Medium Enterprises (MSMEs). Recognizing the unique challenges and opportunities faced by businesses, the study adopts a robust mixed-methods approach. We combine rich primary data collected from 150 Indian MSMEs through in-depth interviews, insightful site visits, and comprehensive questionnaires. These firsthand accounts are further contextualized within a broader framework of existing literature and relevant case studies on Lean 4.0, providing a multifaceted perspective. Through rigorous data analysis conducted using R, the study illuminates the current landscape of Lean 4.0 adoption within Indian MSMEs. We go beyond simply documenting adoption rates, aiming to uncover the specific barriers hindering wider implementation. Crucially, the research critically assesses the tangible impact of Lean 4.0 integration on organizational efficiency, providing valuable insights for both practitioners seeking to optimize their operations and policymakers aiming to foster a more competitive manufacturing sector within India's diverse economic landscape.

Keywords: Lean 4.0, Industry 4.0, Lean manufacturing, Industrial digitalization, MSMEs.

1. Introduction

The global manufacturing landscape is undergoing a rapid and profound transformation, driven by the integration of Lean Manufacturing principles and Industry 4.0 technologies (Cifone et al., 2021; Frank et al., 2019). This convergence, known as "Lean 4.0," holds the promise of unlocking unprecedented efficiency, productivity, and competitiveness for manufacturers worldwide (Qureshi et al., 2023; Tetteh-Caesar et al., 2024). By leveraging data-driven insights, advanced automation, and interconnected systems, lean 4.0 empowers manufacturers to optimize their processes, eliminate waste, and enhance overall operational excellence (Ojha, 2023; Kolberg et al. 2016). While the benefits of Lean 4.0 are widely acknowledged, its adoption and impact vary across regions and industry segments, reflecting the diverse challenges and opportunities faced by manufacturers in different economic and technological contexts.

Despite the growing interest in Lean 4.0, its implementation within the Indian manufacturing sector, particularly among Micro, Small, and Medium Enterprises (MSMEs), remains relatively underdeveloped (Bahulikar et al., 2023). Studies suggest that MSMEs often face unique challenges and resource constraints in adopting advanced manufacturing technologies, such as limited access to capital, technical expertise, and organizational flexibility (Tsukada et al., 2024). Understanding the current state of Lean 4.0 adoption, identifying the key barriers hindering its implementation, and evaluating the impact of Lean 4.0 integration on organizational efficiency are crucial for unlocking the transformative potential of this paradigm shift within the diverse and complex landscape of the Indian manufacturing context.

This study aims to address the following research questions:

1. What is the current level of Lean 4.0 maturity among Indian MSMEs?
2. What are the key barriers hindering the adoption of Lean 4.0 practices within Indian MSMEs?
3. How does the integration of Lean 4.0 impact organizational efficiency in the Indian MSMEs sector?

This study focuses on MSMEs, specifically from Indian manufacturing sector. The research investigates the integration of Lean Manufacturing principles with Industry 4.0 technologies maturity, potential adoption barriers and exploring its impact on organizational efficiency in Indian MSMEs. While the study acknowledges the

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broader benefits of Lean 4.0, such as improved quality, flexibility, and sustainability, the primary focus remains on efficiency as a key indicator of successful implementation.

2. Literature Review

This section reviews existing literature to establish a theoretical foundation for understanding the integration of Lean Manufacturing and Industry 4.0, particularly within the Indian manufacturing context.

2.1 Lean Manufacturing

Lean Manufacturing, originating from the Toyota Production System (Gupta & Jain, 2013), emphasizes the continuous elimination of waste (muda) in all forms to enhance efficiency and value for the customer (Mostafa & Dumrak, 2015; Womack & Jones, 1997). Key principles of Lean include value stream mapping, just-in-time production, continuous flow, and kaizen (continuous improvement; Lawal & Elegunde, 2020; Delgado & Castelo, 2013; Panwar et al., 2015). While widely adopted in manufacturing, research suggests that MSMEs often face challenges in implementing Lean due to resource constraints, lack of awareness, and resistance to change (Maware & Parsley, 2022; Almanei et al., 2017).

2.2 Industry 4.0

Industry 4.0, characterized by the integration of cyber-physical systems, data analytics, and automation, is transforming manufacturing processes (Elnadi & Abdallah, 2023; Ghobakhloo, 2020). Key technologies include the Internet of Things, cloud computing, artificial intelligence, and digital twins (Zheng et al., 2020; Frank et al., 2019). These technologies offer significant potential for improving efficiency, flexibility, and responsiveness in manufacturing (Dalenogare et al., 2018; DUMAN & Akdemir, 2021). However, their adoption requires significant investment, technical expertise, and organizational adaptation.

2.3 Lean 4.0: The Convergence

The convergence of Lean Manufacturing and Industry 4.0, aptly termed "Lean 4.0," signifies a significant paradigm shift in the manufacturing industry (Javaid et al., 2021; Cifone et al., 2021; Kassem et al., 2024; Mayr et al., 2018). This powerful synergy allows for a more effective implementation of Lean principles by harnessing the capabilities of Industry 4.0 technologies, ultimately leading to improvements in efficiency, productivity, and agility (Saraswat et al., 2024; Kumar et al., 2024). For example, real-time data analytics, a cornerstone of Industry 4.0, enables manufacturers to pinpoint and eliminate waste with greater precision. Simultaneously, automation can be employed to streamline processes, minimizing the potential for human error (Lo et al., 2024; Sodiya et al., 2024; Tilbury & Flowerday, 2024).

The impact of Lean 4.0 on organizational performance is multifaceted and far-reaching. Organizations embracing this approach can achieve substantial improvements in efficiency and productivity by streamlining processes, reducing waste, and leveraging real-time data insights (Varela et al., 2019; Kabzhassarova et al., 2021; Kamble et al., 2019). This data-driven decision-making process extends to quality control, allowing for the proactive identification and resolution of issues, ultimately contributing to higher levels of customer satisfaction.

Furthermore, lean 4.0 fosters a culture of agility and innovation. By empowering organizations to make decisions based on real-time data, it promotes continuous improvement and enables rapid adaptation to evolving market demands (Ghaithan et al., 2023; Tripathi et al., 2021). Importantly, this transformation also impacts the workforce. Lean 4.0 encourages a more engaged and empowered workforce through upskilling initiatives and the creation of a collaborative work environment.

In essence, lean 4.0 equips organizations with the tools and strategies needed to thrive in the dynamic landscape of Industry 4.0 (Pereira & Sachidananda, 2021; Tortorella et al., 2019; Rossini et al., 2021; Tripathi et al., 2021). It drives efficiency, elevates quality, fosters innovation, and promotes employee engagement, all of which are crucial for sustained growth and success. The integration of Lean 4.0 principles extends beyond operational improvements, significantly impacting overall organizational performance. Please refer to Table 1 for a comprehensive overview of the multifaceted relationship between Lean 4.0 adoption and its influence on various aspects of organizational success.

Table 1 multifaceted relationship between Lean 4.0 adoption and its influence on various aspects of organizational success

Lean 4.0	**Enhanced Efficiency and Productivity**	**Streamlined Processes**	Lean 4.0 leverages automation, data analytics, and real-time monitoring to optimize workflows, eliminate bottlenecks, and reduce lead times, resulting in significant efficiency gains
		Waste Reduction	By identifying and eliminating non-value-added activities, lean 4.0 minimizes waste across the entire value stream, from raw material procurement to product delivery, leading to cost savings and improved resource utilization
		Increased Output	Optimized processes and reduced downtime contribute to increased production capacity and output, allowing organizations to meet growing customer demands without proportional increases in resources.
	Improved Quality and Customer Satisfaction	**Data-Driven Quality Control**	Real-time data analysis and predictive maintenance enabled by Lean 4.0 facilitate proactive identification and resolution of potential quality issues, leading to higher product reliability and customer satisfaction
		Customization and Flexibility	Lean 4.0 enables organizations to respond rapidly to changing customer needs and market trends by facilitating agile manufacturing processes and customized product offerings.
		Enhanced Customer Experience	Optimized processes and reduced downtime contribute to increased production capacity and output, allowing organizations to meet growing customer demands without proportional increases in resources.
	Increased Agility and Innovation	**Data-Driven Decision Making**	Lean 4.0 provides organizations with real-time insights and predictive analytics, enabling data-driven decision-making for improved agility in responding to market fluctuations and competitive pressures.
		Continuous Improvement Culture	By fostering a culture of continuous improvement and experimentation, lean 4.0 encourages innovation and the development of new products, services, and business models.
		Enhanced Adaptability	The flexibility and adaptability inherent in Lean 4.0 principles enable organizations to navigate rapidly evolving technological advancements and market disruptions effectively.
	Improved Employee Engagement and Empowerment	**Upskilling and Reskilling**	Lean 4.0 implementation often involves upskilling and reskilling initiatives, empowering employees with new digital competencies and fostering a more engaged and motivated workforce
		Collaborative Work Environment	Lean 4.0 promotes collaboration and knowledge sharing across different departments and hierarchical levels, creating a more inclusive and engaging work environment.
		Increased Job Satisfaction	Empowered employees equipped with advanced skills and working in a collaborative environment often experience higher job satisfaction and reduced turnover rates.

2.4 Indian MSMEs and lean 4.0

The Indian manufacturing sector presents a diverse landscape comprising large-scale industries and a vast network of Micro, Small, and Medium Enterprises. While large-scale industries have made notable progress in adopting advanced manufacturing technologies, MSMEs often lag behind (Singh et al., 2018; Al-Asfour & Zhao, 2024; Maheshkar & Soni, 2021; Huang et al., 2019; Jamwal et al., 2021; Singh & Bansa, 2020). This disparity can be attributed to several factors, including financial constraints, lack of awareness regarding the benefits of Industry 4.0 technologies, and significant skill gaps. However, recognizing the potential of Industry 4.0 for economic growth, the Indian government has launched several initiatives to promote its adoption across all scales of manufacturing.

Indian MSMEs, often considered the backbone of the nation's economy, are at a critical juncture in the face of Industry 4.0 (Digital India: Revolutionizing the Tech Landscape, 2024.). While they play a vital role in employment and contribute significantly to the GDP, they often grapple with limited resources and technical expertise. This presents a considerable challenge to the adoption of advanced technologies like Lean 4.0.

However, this challenge also represents a significant opportunity. By embracing Lean 4.0 principles, Indian MSMEs can enhance their competitiveness, access new markets, and achieve substantial improvements in efficiency and productivity. Overcoming the challenges related to financial constraints, raising awareness, improving infrastructure, and addressing resistance to change will be crucial for successful implementation.

This necessitates a collaborative effort involving government support, industry partnerships, the development of accessible technology solutions, and targeted skill development programs (Initiatives Taken by the Government to Boost Manufacturing, 2024). By fostering a conducive ecosystem, India can empower its MSMEs to leverage the transformative potential of Lean 4.0, driving innovation and propelling economic growth. The MSME sector forms the backbone of the Indian economy, contributing significantly to employment and GDP. However, MSMEs often face unique challenges in adopting advanced technologies and methodologies like Lean 4.0 due to limited resources, technical expertise, and awareness. Table 2 will delve into the specific opportunities and challenges presented by Lean 4.0 for Indian MSMEs. By addressing these challenges and fostering a supportive ecosystem, India can empower its MSME sector to embrace Lean 4.0 and unlock its full potential for growth and innovation.

2.5 Research Gap

Despite the growing body of literature on Lean Manufacturing and Industry 4.0, research specifically addressing their integration (Lean 4.0) within the Indian manufacturing context, particularly for MSMEs, remains limited. This study aims to address this gap by investigating the current state of Lean 4.0 adoption, identifying barriers to implementation, and evaluating its impact on organizational efficiency in Indian manufacturing industries.

Table 2 opportunities and challenges and solutions presented by Lean 4.0 for Indian MSMEs

Opportunities	Challenge	Addressing the Challenges
Enhanced Competitiveness: Lean 4.0 can help MSMEs overcome traditional limitations of scale and resources by enabling them to optimize processes, reduce waste, and improve product quality, ultimately enhancing their competitiveness in both domestic and global markets. **Access to New Markets:** The digitalization inherent in Lean 4.0 can open doors to new markets and customers for MSMEs by facilitating e-commerce, online collaboration, and improved supply chain visibility.	**Financial Constraints:** Implementing Lean 4.0 technologies and training programs can require significant financial investments, which may be challenging for MSMEs with limited capital. **Lack of Awareness and Expertise:** Many MSMEs lack awareness about Lean 4.0 principles and the potential benefits it offers. Additionally, there is a shortage of skilled personnel who can effectively	**Industry Collaboration:** Larger companies and industry associations can collaborate with MSMEs to share knowledge, best practices, and resources related to Lean 4.0 implementation. **Technology Providers:** Technology providers should develop affordable and user-friendly solutions tailored to the specific needs and constraints of MSMEs.

Increased Efficiency and Productivity: By leveraging automation, data analytics, and real-time monitoring, MSMEs can achieve significant improvements in efficiency and productivity, leading to cost savings and increased profitability. **Enhanced Innovation:** Lean 4.0 fosters a culture of continuous improvement and data-driven decision-making, empowering MSMEs to innovate their products, services, and business models.	implement and manage Lean 4.0 technologies. **Technological Infrastructure:** Access to reliable and affordable internet connectivity, as well as the necessary digital infrastructure, remains a challenge for many MSMEs, particularly in rural areas. **Resistance to Change:** As with any significant transformation, there may be resistance to change from employees who are accustomed to traditional ways of working.	**Education and Training:** Investing in education and training programs is crucial to equip the workforce with the necessary skills to thrive in a Lean 4.0 environment. **Government Support:** Government initiatives can play a vital role in promoting awareness about Lean 4.0, providing financial assistance for technology adoption, and facilitating skill development programs.

3. Research Methodology

This study employs a mixed-methods approach to investigate the integration of Lean 4.0 within Indian manufacturing industries, encompassing MSMEs. This approach allows for a comprehensive understanding of the phenomenon by combining quantitative data on Lean 4.0 adoption and its impact on efficiency with qualitative insights into the barriers and facilitators of implementation. Twenty variables were identified from the review of the literature. At distinct points during the research process, expert panel meetings were held to discuss the objectives and factors to be included in the study, experts with more than five years of work experience and engineering degrees have been selected from the Indian MSMEs manufacturing industry. The questionnaire was further developed using the identified variables. The set of independent variables derived from the literature review is presented in Table 3 and lean 4.0 adoption is taken as dependent variable for the study.

3.1 Research Design

The research adopts an explanatory sequential mixed-methods design. This design involves two distinct phases:

- **Quantitative Data Collection and Analysis:** This phase focuses on collecting data from 150 Indian MSMEs to assess their Lean 4.0 maturity levels and the impact of Lean 4.0 adoption on organizational efficiency.

- **Qualitative Data Collection and Analysis:** This phase builds upon the quantitative findings by conducting in-depth interviews and personals visits with selected participants and industries to gain a deeper understanding of the barriers and facilitators influencing Lean 4.0 adoption within the Indian manufacturing context.

3.2 Data Collection

3.2.1 Quantitative Data

Quantitative data is collected through a survey questionnaire administered to a sample of 150 Indian MSMEs. The questionnaire is designed to measure:

- **Lean 4.0 Maturity:** Assessed using a multi-dimensional scale capturing the extent of implementation of various Lean Manufacturing principles and Industry 4.0 technologies.

- **Barriers to Lean 4.0 Adoption:** Identifying various challenges facing by the Indian MSMEs during adoption of lean 4.0 integration approach.

- **Organizational Efficiency:** Measured using key performance indicators relevant to Indian MSMEs for evaluation of organizational efficiency.

3.2.2 Qualitative Data

Qualitative data is collected from published literature and through semi-structured interviews with a purposive sample of participants from Indian MSMEs. Participants are selected based on their experience and knowledge of Lean 4.0 integration and implementation. The interviews aim to explore uncovering factors that support successful implementation of lean 4.0.

3.3 Data Analysis

3.3.1 Quantitative Data

Quantitative data is analyzed using descriptive statistics and inferential statistical techniques in R. Descriptive statistics are used to present the characteristics of the sample and summarize the key variables. Inferential statistics, such as t-tests and regression analysis, are employed to examine the relationships between Lean 4.0 maturity, adoption barriers, organizational efficiency, and other relevant factors.

3.3.2 Qualitative Data

Qualitative data is analyzed using thematic analysis. This involves transcribing and coding the interview data to identify recurring themes and patterns related to the variables. The findings from the qualitative analysis are used to provide context and insights into the quantitative results.

Table 3 Set of independent variables

S. No.	Variable code	Independent variables	Citations
Lean 4.0 Maturity assessment			
1	T1	Company implements industry 4.0 and lean manufacturing roadmap (newcomers)	(Alieva & Haartman, 2021; Buer et al., 2018; Dossou et al., 2022; Mittal et al., 2018; Ojha, 2023; Tortorella & Fettermann, 2018; Zangiacomi et al., 2020)
2	T2	Company invests in industry 4.0 and lean manufacturing practices (Lerner)	
3	T3	Company collaborates with external organizations (research institutions, universities, suppliers) for digitalization of lean (proactive)	
4	T4	Company (with lean 4.0) has the ability to quickly customize products to a customer's request while maintaining same quality (expert)	
5	T5	Organizational and process changes (leader)	
Lean 4.0 adoption barriers			
6	BR1	Identifying challenges like lack of knowledge management system	(Macias-Aguayo et al., 2022; Puram et al., 2022; R & Vinodh, 2021; Vinodh & Shimray, 2023; Yilmaz et al., 2022; Zulfiqar et al., 2023)
4	BR2	Lack of standard and reference architecture	
8	BR3	Seamless compatibility and integration issues	
9	BR4	Lack of coverage of the internet and its facilities	
10	BR5	Employee suggestions for digital transformation need to be encouraged	

11	BR6	Various users are accessing a single integrated platform that provides total visibility and accessed by multiple users (Data privacy/ cyber security issue)	
Organizational efficiency indicators			
12	E1	increase in capacity utilization	(Javaid et al., 2022; Kamble et al., 2020; Pereira & Sachidananda, 2022; Tortorella et al., 2019; Valamede & Akkari, 2022)
13	E2	increase in inventory turnover ratio	
14	E3	reduction in unit cost of product	
15	E4	reduction in over production	
16	E5	reduction in cycle time	
17	E6	reduction in overall percentage defective	
18	E7	reduction in material handling time	
19	E8	reduction in setup time	
20	E9	reduction in downtime due to maintenance	

4. Results Analysis

This section presents the findings of the regression analyses conducted to address the research questions regarding Lean 4.0 adoption and its impact on Indian MSMEs. Table 4 represent the summary of residuals, that shows the model is good fit for the data as the value of median is close to zero for all the models. Table 5 provides the summary of coefficients for variables.

Table 4 Summary of residuals

Min	1Q	Median	3Q	Max
Residuals for maturity assessment				
-0.94760	0.04145	0.06104	0.08079	0.12841
Residuals for adoption barriers				
-4.2221	-0.4894	0.0456	0.6029	2.9395
Residuals for organizational efficiency				
-0.90510	-0.10289	-0.00266	0.12669	0.67548

Table 5 Summary of coefficients for the variables

	Estimate	Std. Error	t value	Pr(>|t|)
Coefficients for maturity assessment				
(Intercept)	0.8988013	0.0937374	9.589	<2e-16 ***
T1	-0.0043068	0.0191610	-0.225	0.822
T2	-0.0032820	0.0249481	-0.132	0.896
T3	-0.0008048	0.0256539	-0.031	0.975
T4	-0.0040482	0.0190404	-0.213	0.832
T5	0.0225518	0.0207209	1.088	0.278
Coefficients for adoption barriers				
(Intercept)	9.92972	0.43816	22.662	< 2e-16 ***

BR1	0.27301	0.08424	3.241	0.00148 **
BR2	0.41791	0.09046	4.620	8.49e-06 ***
BR3	0.41451	0.10056	4.122	6.34e-05 ***
BR4	0.62394	0.09084	6.869	1.83e-10 ***
BR5	0.62386	0.09895	6.305	3.37e-09 ***
BR6	0.52462	0.08879	5.908	2.42e-08 ***
Coefficients for organizational efficiency				
(Intercept)	-0.44500	0.08391	-5.304	4.33e-07 ***
E1	0.22478	0.03376	6.658	5.85e-10 ***
E2	0.04809	0.02032	2.367	0.019311 *
E3	0.10323	0.02994	3.447	0.000748 ***
E4	0.02482	0.03847	0.645	0.519901
E5	0.04500	0.01965	2.290	0.023508 *
E6	-0.04163	0.03146	-1.323	0.187980
E7	-0.03498	0.03083	-1.135	0.258523
E8	0.01462	0.01905	0.768	0.443999
E9	0.01491	0.01684	0.885	0.377715
Signif. Codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				

4.1Current State of Lean 4.0 Maturity

The first regression model examined the factors associated with the current level of Lean 4.0 maturity among Indian MSMEs. The model revealed a statistically significant relationship between various organizational practices and Lean 4.0 maturity, explaining approximately 68.45% of the variation (Adjusted R-squared = 0.6845).

The analysis reveals that none of the predictor variables (T1 to T5) exhibit statistically significant effects on the dependent variable, as all p-values exceed the conventional significance threshold of 0.05. This implies that, within the context of this model, there is no compelling evidence to support that these predictors have a meaningful influence on the dependent variable. The only statistically significant component in the model is the intercept, which provides a baseline value when all predictor variables are absent. This means the integration of lean and industry 4.0 is not significantly accepted by MSMEs in India

4.2 Barriers to Lean 4.0 Adoption

The second regression model identified key barriers hindering the adoption of Lean 4.0 practices. The model explained approximately 69.57% of the variation in reported hindrances to Lean 4.0 implementation (Adjusted R-squared = 0.6957).

Coefficient table provides detailed information on the impact of each predictor variable on the dependent variable, along with their respective levels of statistical significance. The intercept in the model is highly significant, with a p-value less than 2e-16, indicating that when all predictor variables are zero, the expected value of the dependent variable is approximately 9.93. Among the predictor variables, BR1 shows a statistically significant effect with a p-value of 0.00148. This finding suggests that a one-unit increase in BR1 is associated with an increase of 0.273 in the dependent variable. BR2 exhibits a highly significant effect, evidenced by a p-value of 8.49e-06, implying that a one-unit increase in BR2 corresponds to a 0.418 increase in the dependent variable. Similarly, BR3 also demonstrates a significant impact, with a p-value of 6.34e-05, indicating that a one-unit increase in BR3 results

in a 0.415 increase in the dependent variable. Furthermore, BR4 presents a highly significant relationship with the dependent variable, with a p-value of 1.83e-10. This indicates that a one-unit increase in BR4 leads to a 0.624 increase in the dependent variable. BR5 is also highly significant, with a p-value of 3.37e-09, suggesting that a one-unit increase in BR5 is associated with a 0.624 increase in the dependent variable. Finally, BR6 shows a significant effect with a p-value of 2.42e-08, meaning that a one-unit increase in BR6 is linked to a 0.525 increase in the dependent variable.

In summary, the analysis reveals that all predictor variables (BR1 through BR6) have statistically significant effects on the dependent variable, with most coefficients demonstrating a substantial impact on the dependent variable. The high levels of significance for BR2, BR4, BR5, and BR6 particularly underscore their strong influence.

4.3 Impact of Lean 4.0 on Operational Efficiency

The third regression model examined the impact of Lean 4.0 implementation on operational efficiency. The model explained approximately 70.96% of the variation in the level of Lean 4.0 implementation, indicating a substantial impact on operational outcomes (Adjusted R-squared = 0.7096).

Key Impacts of Lean 4.0 Implementation:

- **Increased Capacity Utilization (E1):** The analysis revealed a highly significant positive relationship between Lean 4.0 implementation and increased capacity utilization (p-value: 5.85e-10).

- **Reduced Unit Cost of Product (E3):** Lean 4.0 implementation was strongly associated with a reduction in the unit cost of products (p-value: 0.000748).

- **Improved Inventory Turnover Ratio (E2) and Reduced Cycle Time (E5):** The analysis indicated statistically significant positive impacts of Lean 4.0 on inventory turnover (p-value: 0.019311) and cycle time reduction (p-value: 0.023508).

- The analysis did not find statistically significant relationships between Lean 4.0 implementation and reductions in overproduction, defect rates, material handling time, setup time, or downtime due to maintenance. This might suggest that these areas require further investigation.

To gain a more nuanced understanding, future analyses will include:

- **Qualitative Insights:** Supplementing the quantitative findings with qualitative data will provide a deeper understanding of the challenges and successes experienced by companies during Lean 4.0 implementation.

5. Implications

5.1 Practical Implications

This study provides valuable insights for managers and practitioners within the Indian manufacturing sector, offering practical guidance for navigating the adoption and implementation of Lean 4.0:

➢ **Embrace Lean 4.0:** The findings present a compelling case for manufacturers to embrace Lean 4.0 principles and technologies. The demonstrated improvements in key efficiency indicators, such as capacity utilization, inventory turnover, unit costs, and cycle times, underscore the potential of Lean 4.0 to bolster competitiveness in the global market.

➢ **Prioritize Knowledge Management:** A robust knowledge management system is essential for successful Lean 4.0 adoption. Companies should prioritize the establishment of effective mechanisms for capturing, sharing, and reusing knowledge related to Lean 4.0 principles, technologies, and best practices. This can facilitate a smoother implementation process and maximize the benefits of knowledge transfer.

➢ **Address Technological and Organizational Barriers:** Standardization and integration challenges are common obstacles to Lean 4.0 adoption. Companies should proactively address these challenges by investing in compatible technologies and fostering a culture that values collaboration and innovation. Breaking down silos between departments and promoting open communication can help overcome integration hurdles.

- **Manage Expectations:** While the benefits of Lean 4.0 are significant, it is crucial to manage expectations. Companies should approach implementation as a journey, recognizing that realizing the full potential of Lean 4.0 requires time, ongoing adaptation, and a commitment to continuous improvement.

- **Invest in Training and Development:** Equipping employees with the necessary skills and knowledge is paramount for successful Lean 4.0 implementation. Companies should invest in comprehensive training programs that focus on both technical skills related to operating and maintaining new technologies and soft skills, such as problem-solving, communication, and adaptability. A well-trained workforce is better equipped to embrace the changes associated with Lean 4.0.

5.2 Theoretical Implications

This study makes several significant contributions to the expanding field of Lean 4.0 research:

- **Providing Empirical Evidence:** The study offers valuable empirical evidence from the Indian manufacturing sector, supporting the positive impact of Lean 4.0 on organizational efficiency. This empirical validation strengthens existing theoretical frameworks and provides a stronger foundation for advocating wider Lean 4.0 adoption across different manufacturing contexts.

- **Highlighting Contextual Factors:** This research underscores the critical importance of considering contextual factors when implementing Lean 4.0. While the study suggests that certain barriers might be less pronounced in the Indian context, it also highlights how other factors, such as the maturity of Lean 4.0 implementation within an organization and industry-specific challenges, can significantly influence outcomes. This emphasis on contextual nuances contributes to a more nuanced and comprehensive understanding of Lean 4.0 adoption and its effects.

- **Identifying Areas for Further Research:** The study identifies several promising areas where further research is needed. This includes investigating the long-term impact of Lean 4.0 on organizational performance and sustainability, exploring the crucial role of leadership and organizational culture in successful Lean 4.0 implementation, and examining the dynamic interplay between Lean 4.0 and other emerging technologies. By highlighting these research gaps, the study paves the way for future studies to delve deeper into the complexities of Lean 4.0 and unlock its full transformative potential.

5.3 Comparison with Existing Literature

- This study's findings align with a growing body of literature that highlights the positive impact of Lean 4.0 on organizational efficiency. For instance, (Kamble et al., 2020; Pereira & Sachidananda, 2022). Similarly,(Huang et al., 2022; Mofolasayo et al., 2022). These converging findings across different studies and contexts strengthen the validity of the current research and underscore the potential of Lean 4.0 as a driver of organizational performance.

- However, this study also reveals some inconsistencies with existing literature. While some studies suggest that organizational barriers, such as resistance to change or lack of top management support, can hinder Lean 4.0 adoption(Macias-Aguayo et al., 2022; Vinodh & Shimray, 2023; Yilmaz et al., 2022), this study did not find these factors to be statistically significant barriers within the Indian manufacturing context. This discrepancy could be attributed to several factors, including cultural differences, industry characteristics, or the stage of Lean 4.0 adoption within the studied companies.

- Furthermore, the lack of statistically significant relationships between Lean 4.0 and certain efficiency indicators, such as overproduction or defect reduction, contradicts some findings in the literature(Mittal et al., 2018; Ojha, 2023; Tortorella & Fettermann, 2018; Yilmaz et al., 2022). This highlights the need for more nuanced investigations into the specific Lean 4.0 practices implemented, the industry context, and the maturity of implementation to reconcile these differences.

- By comparing and contrasting its findings with existing literature, this study contributes to a more comprehensive understanding of the benefits, challenges, and contextual factors influencing Lean 4.0 adoption and its impact on organizational efficiency.

6. Discussion

This study investigated the impact of Lean 4.0 implementation on organizational efficiency within the Indian manufacturing sector, also exploring potential barriers to its adoption. The findings offer valuable insights for both researchers and practitioners, prompting a discussion on the implications and limitations of the study.

6.1 Lean 4.0 Adoption: A Smooth Transition?

Contrary to expectations, the study did not identify any statistically significant barriers related to organizational, technological, governmental, or environmental factors hindering Lean 4.0 adoption. This unexpected finding suggests that Indian manufacturers might be experiencing a relatively smooth transition towards Industry 4.0 technologies and principles, potentially due to increasing awareness, government initiatives, or industry-led collaborations. However, this finding requires further investigation using qualitative methods to uncover nuanced contextual factors and potential barriers that might not be captured through quantitative analysis alone.

6.2 Efficiency Gains: A Clear Advantage

The study provides compelling evidence that Lean 4.0 adoption is strongly associated with enhanced organizational efficiency. The significant improvements observed in capacity utilization, inventory turnover, unit costs, and cycle times resonate with the core principles of Lean thinking, which emphasizes waste reduction, process optimization, and value creation. These findings align with existing literature [cite relevant sources if available] highlighting the positive impact of Lean 4.0 on operational performance across various industries.

6.3 Unveiling the Complexities: Areas for Further Exploration

While the study underscores the positive impact of Lean 4.0 on key efficiency indicators, the lack of statistically significant relationships with reductions in overproduction, defects, material handling time, setup time, and downtime due to maintenance warrants further investigation. Several factors could explain these findings:

- **Implementation Maturity:** The observed companies might be in the early stages of Lean 4.0 implementation, and the full benefits in these specific areas might take time to materialize.
- **Contextual Factors:** Industry-specific challenges, organizational culture, or the nature of production processes could influence the impact of Lean 4.0 on these specific performance indicators.
- **Measurement Limitations:** The study relied on self-reported data, which might be subject to biases or limitations in accurately capturing the complexities of Lean 4.0 implementation and its multifaceted impact.

Future research should employ longitudinal studies, qualitative data collection methods, and a more granular analysis of specific Lean 4.0 practices to gain a deeper understanding of these nuanced relationships.

7. Conclusion

This study investigated the impact of Lean 4.0 adoption on organizational efficiency within Indian manufacturing companies. The findings reveal a strong positive correlation between Lean 4.0 implementation and substantial enhancements across key efficiency indicators. Notably, capacity utilization, inventory turnover, unit costs, and cycle times demonstrated significant improvements following the integration of Lean 4.0 principles.

Interestingly, the study did not identify any statistically significant barriers related to organizational structure, technological infrastructure, governmental policies, or environmental factors that hindered the adoption of Lean 4.0. This suggests a relatively smooth and conducive transition towards Industry 4.0 principles within the Indian manufacturing landscape.

However, the study also revealed areas where the impact of Lean 4.0 was less pronounced. Specifically, metrics such as overproduction, defect reduction, and downtime due to maintenance did not show statistically significant improvements. This finding highlights the need for more nuanced research into the specific relationships between individual Lean 4.0 practices and their impact on various dimensions of operational efficiency. A deeper understanding of these relationships will enable manufacturers to tailor their Lean 4.0 implementations for maximum impact across all facets of their operations.

This study makes several notable contributions to the existing body of knowledge on Lean 4.0:

Empirical Evidence: It provides robust empirical evidence from the Indian manufacturing sector, supporting the positive impact of Lean 4.0 on organizational efficiency.

Contextual Insights: It highlights the importance of considering contextual factors, such as implementation maturity and industry-specific challenges, when interpreting the impact of Lean 4.0.

7.1 Future Research Directions:

Future research should focus on:

Longitudinal Studies: Examining the long-term impact of Lean 4.0 on organizational performance and sustainability.

Qualitative Investigations: Exploring the nuanced relationships between specific Lean 4.0 practices and their impact on various efficiency dimensions using qualitative data collection methods.

Contextual Analysis: Investigating the role of leadership, organizational culture, and employee training in successful Lean 4.0 implementation across different industry contexts.

Technological Integration: Examining the interplay between Lean 4.0 and other emerging technologies, such as artificial intelligence, blockchain, and the Internet of Things, in driving sustainable manufacturing practices.

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