

Modernizing Lean in the Automotive Industry: A Literature Review of Digitalization, Resilience, and Sustainability

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Abstract

Lean manufacturing has long been a central paradigm of efficiency and competitiveness in the automotive industry. However, the accelerating pressures of digital transformation, global supply chain disruptions, and sustainability imperatives are challenging and reshaping traditional lean practices. This literature review synthesizes recent scholarly research on lean manufacturing in the automotive sector, focusing on three critical themes: digitalization, resilience, and sustainability. Findings suggest that lean is no longer understood merely as a set of efficiency-oriented tools but as an evolving system that must integrate data-driven technologies, risk-management strategies, and environmental and human-centered concerns. The review highlights key tensions between efficiency and resilience, simplicity and digital complexity, and cost reduction and sustainability. It concludes with an integrative framework for lean's modernization and identifies promising directions for future research in the automotive context.

Keywords: lean manufacturing, automotive industry, digital transformation, supply chain resilience, sustainability, Industry 4.0, human-centered lean

Introduction

Lean manufacturing, as formalized in the Toyota Production System (TPS), has defined global manufacturing practice since the mid-20th century. It emphasizes the elimination of waste (muda), the continuous improvement of processes (kaizen), just-in-time (JIT) inventory management, and worker involvement in process optimization. In the automotive industry, lean has delivered remarkable gains in quality, productivity, and competitiveness. The diffusion of lean principles beyond Japan to North America and Europe was documented in influential works such as Womack, Jones, and Roos's *The Machine That Changed the World* (1990), which demonstrated lean's superiority over mass production in cost, quality, and adaptability.

Nevertheless, lean manufacturing has faced critical challenges in the past decade. The COVID-19 pandemic exposed vulnerabilities in tightly coupled, low-inventory systems. Semiconductor shortages and logistical disruptions highlighted the risks of

excessive reliance on JIT. Meanwhile, the emergence of Industry 4.0 technologies, including the Internet of Things (IoT), artificial intelligence, big data analytics, and digital twins, has created both opportunities and tensions in lean practice. At the same time, environmental sustainability and human-centered management have become pressing imperatives in the automotive sector, driven by regulatory, consumer, and societal pressures.

This review seeks to synthesize contemporary literature on lean manufacturing in the automotive sector, with special attention to three areas where traditional lean is being transformed: digitalization, resilience, and sustainability. The guiding questions are how digital technologies are reshaping lean principles, how lean is being adapted to ensure resilience against disruptions, and how lean is being integrated with sustainability and human-centered approaches.

Methodology

Research Approach

This study employs a narrative literature review approach to synthesize existing knowledge on lean manufacturing transformation in the automotive industry. Unlike systematic reviews that follow rigid protocols, this methodology allows for a comprehensive exploration of diverse perspectives and emerging themes across the three focal areas: digitalization, resilience, and sustainability.

Literature Search Strategy

Database and Search Platform: The literature search was conducted using Google Scholar as the primary database, selected for its comprehensive coverage of academic publications, including peer-reviewed journals, conference proceedings, and recent working papers that capture emerging trends in lean manufacturing.

Search Terms: The search strategy employed a combination of keywords using Boolean operators:

("lean manufacturing" OR "lean production" OR "Toyota Production System")

AND ("automotive" OR "automobile" OR "car manufacturing")

AND ("digitalization" OR "digital transformation" OR "Industry 4.0" OR "resilience" OR "sustainability" OR "green lean")

Selection Criteria

Inclusion Criteria:

Studies focused on automotive industry applications

- Research addressing lean manufacturing in relation to digitalization, resilience, or sustainability

- Publications in English language
- Theoretical and empirical studies

Exclusion Criteria:

- Non-academic sources (blogs, news articles, company reports)
- Studies focused solely on other industries without automotive relevance
- Purely technical papers without managerial implications

Literature Analysis Process

A three-step approach was followed for the analysis. Titles and abstracts were reviewed for relevance to the research focus. Then selected papers were read in full and assessed for quality and contribution. In the final step, the findings were integrated to develop conceptual insights and future research direction

Literature Review

Foundations of Lean Manufacturing

Lean manufacturing emerged most prominently in the Japanese automotive industry in the post-World War II period. Toyota's system emphasized waste elimination, respect for people, and standardized processes. Scholars have consistently emphasized that lean is not only a set of technical tools but also a philosophy of continuous improvement and problem solving (Liker, 2004). Empirical research has documented lean's positive impact on cost reduction, quality enhancement, and flexibility in automotive manufacturing (Shah & Ward, 2007). Yet even in its early adoption in the West, lean faced critiques of excessive worker pressure, difficulties in cultural transfer, and potential fragility in highly optimized supply systems (Hines, Holweg, & Rich, 2004). These critiques foreshadowed later debates on lean's limitations under global uncertainty.

Digitalization and Lean Transformation

The emergence of Industry 4.0 has generated significant debate on the relationship between digital transformation and lean principles. Schumacher, Bildstein, and Bauernhansl (2019) argue that digital technologies impact lean production systems at multiple levels, including strategy, methods, and shop-floor integration. Their study suggests that the integration of data analytics, sensors, and cyber-physical systems changes how waste is identified and eliminated, making lean systems more data-driven and predictive rather than reactive.

Scriven and colleagues (2024) propose a framework for lean digital transformation, emphasizing that digital tools can enhance traditional lean objectives by improving visibility, enabling real-time decision making, and increasing responsiveness. However, they also caution that excessive digitalization can create "digital waste"

through redundant measurement and data overload, potentially undermining lean's emphasis on simplicity and clarity. Schröder, Mokudai, and Holst (2024) provide a comparative perspective on German and Japanese automotive industries, showing that while both are integrating digital technologies into lean systems, their approaches differ. German firms tend toward top-down, large-scale digital initiatives, while Japanese firms favor bottom-up experimentation aligned with kaizen culture.

Other studies have highlighted specific automotive processes. Yang, Wang, and Wu (2025) applied value stream mapping in the body painting process of new energy vehicles, integrating digital monitoring to identify waste and improve emissions purification. Their findings demonstrate how lean combined with digital transformation can deliver measurable environmental as well as productivity benefits.

The literature suggests that digital technologies enhance lean by enabling predictive maintenance, real-time supply chain visibility, and automated defect detection, but integration costs, workforce skill gaps, and cultural resistance remain significant barriers. There is a growing recognition that digitalization is not a replacement for lean but a complementary force that reshapes lean's core practices.

Resilience and Lean under Disruption

The COVID-19 pandemic has intensified scholarly attention on the tension between lean efficiency and supply chain resilience. Xu et al. (2020) and Raj et al. (2022) show how global supply chains experienced severe breakdowns due to supplier shutdowns, transportation bottlenecks, and sudden demand shocks. Automotive firms that relied heavily on JIT practices faced acute disruptions, as missing components such as semiconductors halted production of high-value vehicles.

Fogliatto et al. (2024) argue that lean practices can in fact support resilience by promoting strong supplier relationships, visual management, and continuous improvement routines. However, they acknowledge that resilience requires modifications to pure lean, including selective buffers, redundant sourcing, and proactive risk mapping. Qamar et al. (2025) similarly find that automotive supply chains have begun reintroducing buffer strategies after COVID-19, moving toward a hybrid of just-in-time and just-in-case. Hosseini Shekarabi, Kiani Mavi, and Macau (2025) highlight the role of digital technologies such as machine learning and digital twins in enhancing supply chain resilience, emphasizing that resilience is increasingly understood as a function of both lean practices and technological augmentation.

These studies collectively indicate that lean and resilience are not mutually exclusive but must be reconciled through hybrid models. Traditional lean's strict elimination of slack is giving way to a more nuanced approach where efficiency is balanced with redundancy and risk-preparedness.

Sustainability and Human-Centered Lean

Sustainability has become an indispensable dimension of lean in the automotive sector. Scholars have increasingly examined how lean can be integrated with environmental and social performance objectives. Sharma et al. (2021) conducted a systematic review of lean, agile, resilient, and green paradigms, concluding that lean and green practices are often synergistic, particularly in reducing energy use and resource consumption. However, they also note tensions where environmental requirements impose additional costs or complexity.

Recent research extends this integration to emerging sectors such as electric vehicles. Yang et al. (2025) found that lean methods combined with digital technologies not only improved throughput but also enhanced exhaust gas purification, directly linking lean practices with environmental outcomes. Hines, Magnani, Mula, and Sanchis (2025) propose a model of “lean Industry 5.0,” which emphasizes human-centeredness alongside efficiency and digitalization. Their framework integrates worker participation, ergonomic design, and social sustainability with technological augmentation, marking a significant departure from lean’s earlier cost-dominated image.

Despite these advances, gaps remain. There is relatively little empirical measurement of worker well-being, job satisfaction, or skill development in lean environments enhanced by automation. Likewise, while environmental performance metrics such as carbon emissions and energy use are beginning to be studied, more comprehensive life-cycle assessments of lean practices are still needed in the automotive industry.

Discussion

The reviewed literature shows that lean manufacturing is no longer a static paradigm of efficiency but an evolving system influenced by digital technologies, global disruptions, and sustainability pressures. Several integrative insights can be drawn. First, digital transformation is reshaping lean rather than displacing it. Sensors, predictive analytics, and digital twins enhance waste elimination and quality management by providing real-time data and predictive capabilities. However, there is a risk of undermining lean’s simplicity with excessive complexity and cost. Second, resilience has become a central concern. While lean historically emphasized minimizing inventory and slack, the pandemic demonstrated that some level of redundancy is necessary to withstand shocks. Scholars now propose hybrid models that combine lean efficiency with just-in-case resilience strategies, supported by digital visibility and monitoring. Third, sustainability and human-centered approaches are no longer peripheral but central to lean’s legitimacy. Environmental regulations, corporate social responsibility, and consumer expectations push firms to integrate green practices and social considerations into lean systems. Emerging literature on Industry 5.0 suggests that worker well-being, agency, and ergonomic

design must accompany technological augmentation for lean to remain sustainable in the long term.

These developments indicate a conceptual shift from lean as a narrow cost-efficiency system toward what might be termed “Lean 4.0,” integrating digitalization, resilience, and sustainability. Yet the literature also reveals tensions. Lean’s traditional emphasis on cost reduction can conflict with investments in redundancy and green technologies. Digital augmentation can create information overload and high costs, challenging lean’s goal of simplicity. Moreover, there is a lack of longitudinal studies tracking how firms actually implement and sustain hybrid lean systems over time.

Conclusions

This literature review demonstrates that lean manufacturing in the automotive industry remains central but is undergoing significant transformation. Digitalization is enhancing lean practices through real-time monitoring and predictive capabilities, resilience is being integrated through hybrid just-in-time and just-in-case strategies, and sustainability is increasingly embedded through green and human-centered lean approaches. These changes suggest that lean should be reinterpreted not merely as a toolkit for efficiency but as a broader socio-technical system balancing efficiency, resilience, and sustainability.

For researchers, the review highlights the need for further studies that integrate lean with digital and resilience theories, longitudinal analyses of lean transformation in practice, and comprehensive metrics that capture environmental and social as well as economic outcomes. For practitioners, the findings suggest that automotive firms should view lean as an evolving system that must be continuously adapted, investing not only in traditional waste elimination but also in technological capabilities, risk management, and human-centered design.

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