Integrating Industry 5.0 Paradigms within Lean Manufacturing Principles

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Abstract

Manufacturing operations management continuously strives for competitiveness and adaptability. While Lean 4.0 primarily leveraged digitalization for efficiency gains, this paper addresses the critical research gap concerning the lack of a prescriptive, normative conceptual model capable of structurally aligning Lean principles with the three core tenets of Industry 5.0: human-centric, resilience and sustainability. A theory-building approach utilizing systematic conceptual analysis and the axiomatic design methodology was employed. This methodology maps conventional Lean principles against the Industry 5.0 pillars, enabling the derivation of a novel, multidimensional framework: the Lean 5.0 parameter integration matrix. This matrix formalizes design using the axiomatic design independence axiom, providing a mathematical basis to decouple conflicting efficiency and human-centric goals. The paper details the operational mechanisms for key Lean 5.0 tools that utilize advanced technologies like explainable artificial intelligence and collaborative robotics to achieve normative Industry 5.0 outcomes. The framework's effectiveness is validated through an empirical case study in an additive manufacturing environment. The quantitative results demonstrate that implementing the Lean 5.0 parameter integration matrix successfully resolved a critical design contradiction, leading to a 77% reduction in mean time to recovery and a 74% reduction in setup error rate, all while maintaining or slightly improving overall operational efficiency. The Lean 5.0 parameter integration matrix provides the essential structural framework for the next generation of human-centric, resilient and sustainability manufacturing.

Highlights:

- Human-Centricity mandates technology augments, not replaces, human roles.
- Lean 5.0 structurally aligns waste elimination to target Carbon Muda.
- Multi-dimensional framework established the new Lean 5.0 paradigm.
- Operational mechanisms for key Lean 5.0 tools are introduced.
- Prescriptive model aligns Lean principles with Industry 5.0 pillars.

1. Introduction

Manufacturing and service sectors actively strive for competitive advantage by delivering value-added services and achieving operational excellence. These endeavors are fundamentally anchored in optimizing efficiency, rigorously reducing waste, and strategically employing technology to augment human capabilities. Concurrently, ongoing industrial revolutions underscore the critical importance of leveraging advanced technological paradigms and aligning them with established operational principles to achieve resilient, sustainable, and human-centric progress [1], [2]. The Lean Manufacturing approach has long been a core strategy for minimizing waste and enhancing efficiency across diverse operations [3]. Among established strategies, Lean Manufacturing, originating in the Third Industrial Revolution, has consistently driven operational excellence [4]. The subsequent integration of Lean principles with the Fourth Industrial Revolution (Industry 4.0) marked a major technological step forward. Characterized by the convergence of cyber-physical systems, the Internet of Things (IoT), big data, and artificial intelligence, this confluence led to the concept of Lean 4.0 [5], [6], enabling Lean Manufacturing's adaptation to modern technologies. Lean 4.0 successfully maximized operational efficiency and waste reduction by utilizing real-time data in smart manufacturing environments [7], [8]. This critical development expanded its tools, such as Value Stream Mapping 4.0 (VSM 4.0) [9] and SMED 4.0 [10], through data-driven methods.

Building upon Industry 4.0's advancements in automation and digital efficiency, the Fifth Industrial Revolution (Industry 5.0), materializing in the early 2020s [11], [12], represents a qualitative shift in normative values, not merely a technological upgrade. Industry 5.0 fundamentally distinguishes itself from Lean 4.0 by shifting the primary mandate from pure technological efficiency to broader societal and environmental value [13], [14]. It re-centers human collaboration and well-being, prioritizing Human-Centric (valuing skills and human-machine synergy [15]), Environmental Sustainability (minimizing ecological impact), and Operational Resilience (enhancing robust, adaptable production systems [16]). Consequently, comprehending the effective integration of established Lean methodologies within this evolving, human-centric, and resilient industrial paradigm constitutes a critical domain for academic inquiry.

Given the operational imperative of Lean and the normative goals of Industry 5.0, the necessity for their integrated synergy is increasingly apparent. While Lean 4.0 provided a technological roadmap for efficiency, it often minimized the human element and lacked the structural mechanisms for achieving holistic sustainability and resilience. This results in a critical research gap: there is a lack of a theoretically grounded, prescriptive conceptual model that structurally and operationally aligns Lean's principles with the three core normative pillars of Industry 5.0 (Human-Centric, Resilience, Sustainability). This research systematically addresses this gap. The originality of this work is underscored by its objective to construct a comprehensive conceptual model that elucidates all critical intersections and provides actionable blueprints. This work's contribution includes proposing an Integrated Lean 5.0 Framework that is derived through a systematic conceptual methodology, ensuring its structure is theoretically justified against the three I5.0 pillars. It also provides detailed operational conceptualizations for key "Lean 5.0" tools, defining the specific technological and human-centric mechanisms that achieve 5.0 outcomes, thereby clarifying their novelty over Lean 4.0 implementations. Finally, it offers a comprehensive set of multi-dimensional Key Performance Indicators designed to measure the success of I5.0's normative alignment. This research is poised to make a significant contribution to the fields of industrial engineering and advanced manufacturing systems.

The paper is structured as follows: A critical review of the existing literature is presented. Next, the systematic methodology for conceptual framework derivation is outlined. This is followed by a presentation of the findings, including the Integrated Lean 5.0 Framework and the operationalized tools. The empirical case study is then presented to validate the framework's effectiveness. Subsequently, the analysis, critical discussion, and managerial implications are provided. Finally, the conclusion is offered, outlining the future validation roadmap for advanced manufacturing.

2. Literature Review

The literature review sheds light on the evolution of Lean through Industry 3.0, its integration with Industry 4.0 technologies, and its future within Industry 5.0. As shown in Figure 1, the framework of the literature review covers these domains.
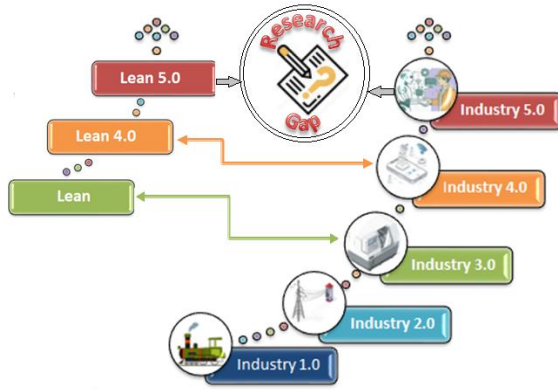
Figure 1. *Mapping the Literature and Research Gap*

2.1 Lean Manufacturing

Lean manufacturing, also known as the Toyota Production System (TPS), maximizes customer value by systematically eliminating waste in manufacturing and service processes [17], [18]. Pioneered at Toyota during the mid-20th century, this methodology evolved alongside Industry 3.0, embracing mass production and automation [19], [20].

The Lean philosophy centers on continuous improvement and respect for people. This drives the systematic removal of "non-value-added activities," famously known as the "8 Wastes" [21], [22]. Dedicated Lean tools, such as Just-in-Time, Poka-Yoke, and Total Productive Maintenance, address each type of waste, significantly enhancing efficiency [23], [24].

Lean has been implemented across various industries [25], services [26], healthcare [27], construction [28], and education [29]. Its widespread success further emphasizes correct tool selection and implementation for effective waste reduction [30], [31], [32]. However, while foundational, traditional Lean often faces scalability and real-time data challenges in increasingly complex industrial environments, indicating a clear need for modern adaptations [33], [34].

2.2 Lean 4.0

Industry 4.0, introduced at the 2011 Hannover Fair [35], transforms manufacturing by leveraging smart technologies. Combining traditional Lean's strengths with Industry 4.0's real-time data and advanced analytics, this integration simplifies operations and boosts responsiveness, and is known as Lean 4.0 [36], [37].

Digitalization of Lean tools, like Value Stream Mapping 4.0, optimizes processes through real-time data and automation [38], [39]. Robust Lean practices facilitate Industry 4.0 adoption [40], impacting Lean automation, smart factories, and security via decentralized production and cyber-physical systems [41]. Practical applications demonstrate improvements, such as minimizing production losses in various industries [42], while recent work further aids decision-makers in jointly implementing Lean and Industry 4.0 by identifying feasible combinations and pathways [43], [44].

However, despite leveraging advanced analytics and algorithms, Lean 4.0 faces inherent barriers: it often downplays the human element, overlooks holistic sustainability, and lacks true resilience to disruption [45], [46]. These limitations necessitate Lean's evolution to prioritize human-centric, broader sustainability, and enhanced resilience in its next paradigm.

2.3 Lean 5.0 Progress

Industry 5.0, introduced by the European Commission in 2021 [47], extends Industry 4.0 by explicitly prioritizing human-centric, resilience, and sustainability [48], [49]. The human-centric principle focuses on highlighting the role and contribution of humans in operations, recognizing that empowering human creativity, problem-solving, and adaptability is key to unlocking new forms of value creation [50], [51]. Research shows that simulation modeling in human-robot collaboration reduces waste and boosts productivity [52], while collaborative disassembly in smart manufacturing contributes to creating flexible, eco-friendly manufacturing processes [53].

From a resilience perspective, Industry 5.0 aims to instill robustness and adaptability. Studies focus on factors that enhance the resilience of manufacturing companies during disruptions, highlighting digital technologies and supply chain integration [54. A proposed Lean 5.0 Axiomatic Design framework to integrate human-centric, resilience, and sustainability principles into the inventive design of manufacturing systems [55]. Integrating monitoring-enabled digital technologies with human factors leads to a significant enhancement in system resilience, supporting value creation and waste reduction [56].

Sustainability is vital for achieving long-term value. New tools for measuring Circular Economy implementation demonstrate how industrial symbiosis

reduces waste and enhances value [57], with a special focus on reducing carbon emissions and improving consumed energy flow [58], [59]. Optimizing processes through raw material reuse also minimizes waste and increases added value [60].

Despite these aspirations, Industry 5.0 currently lacks comprehensive methods, defined implementation methodologies, and precise adaptability analyses for existing Lean tools and strategies. Future research is critically needed to develop specific Lean 5.0 tools and Key Performance Indicators.

3. Research Methodology

A qualitative, theory-building research approach is employed in this study, utilizing systematic conceptual analysis to develop a robust and novel framework for Lean-Industry 5.0 integration. The methodology focuses on the systematic alignment and synthesis of established theoretical principles (Lean Manufacturing) with the emerging normative paradigm (Industry 5.0) to construct an integrated model whose structure is theoretically justified. This approach specifically addresses the critical need for a prescriptive, normative model, moving beyond descriptive observations of technological convergence. he conceptual methodology progresses through three interconnected and sequential phases: Theoretical Mapping, Derivation of Integration Dimensions, and Operationalization.

3.1 Theoretical Mapping and Core Requirements

This phase establishes the foundational and normative requirements for integration by systematically synthesizing the core principles of both paradigms.

The fundamental operational requirements of Lean Manufacturing rest on three core axes, detailed in Table 1.

Table 1. Core lean principles for effective integration.

Requirement	Description
Customer Value Focus	Ensuring integration adds value to the end customer
Continuous Waste Elimination	Identifying and eliminating factors that hinder flow
Achieving Continuous Flow and Pull Systems	Designing processes that streamline information and materials

Commitment to Continuous Improvement	Enhancing continuous enhancement within integrated systems
Respect for and Empowerment People	Highlighting the importance of empowering individuals for success

The Industry 5.0 core pillars (Human-Centric, Resilience, and Sustainability) are established as the normative requirements and strategic guiding philosophies as illustrated in Table 2.

Table 2. Core Industry 5.0 Pillars for Effective Integration.

Requirement	Description
Human-Centric	Enhancing human-machine collaboration and workforce well-being
Resilience	Enabling systems to adapt to changes and support supply chain agility
Sustainability	Ensuring integration supports resource efficiency and circular economy principles

They define the system's high-level objectives that the operational Lean principles must structurally achieve.

3.2 Derivation of Integration Dimensions

This phase represents the core methodological step for establishing the framework's theoretical novelty and rigor. The six Integration Dimensions are not a mere compilation but are strategically derived from the systematic analysis of the necessary intersections and theoretical gaps between the principles established in Phase I.

The derivation process involved analyzing the synergistic potential and necessary bridging mechanisms across three channels. Direct Synthesis, where dimensions were created when core principles directly overlap or are mutually dependent (e.g., the synergy between Lean's Respect for People and Industry 5.0's Human-Centric necessitates the Human and Cultural Dimension). Bridging Mechanisms and Enablers, where dimensions represent the necessary infrastructure and governance required to achieve the new normative goals. And finally, evaluation mechanism, where dimensions were created to define the necessary structural changes and evaluation metrics. The resulting six integration dimensions, therefore, form the theoretically justified structural

axes of the proposed conceptual framework as presented in Table 3.

Table 3. Key dimensions for Lean-Industry 5.0 integration.

Integration Dimension	Description
Technological Dimensions	How technologies enhance and integrate practices
Human and Cultural Dimension	Impact on workforce roles, skills, culture and well-being
Organizational and Operational Dimension	Adjustments to structures and decision-making
Resilience, Business Continuity and Risk Management Dimension	Enhancing supply chain continuity and risk mitigation
Environmental and Sustainability Dimension	Contribution to green practices and resource efficiency
Economic and Business Dimension	Impact on financial performance and new business models

3.3 Derivation of Integration Dimensions

This final phase translates the theoretically derived dimensions into practical, actionable, and measurable constructs. Guided by the six integration dimensions, the conceptualization of Lean 5.0 tools involved systematically augmenting traditional Lean tools with specific, advanced Industry 5.0 technologies. This ensures the operational mechanisms of the tools directly address the prescriptive requirements of the derived dimensions.

Key performance indicators were formulated to provide a rigorous evaluation methodology. These metrics are specifically designed to be multi-dimensional, covering economic, environmental, social, and operational facets, thereby linking the framework's performance directly back to the successful fulfillment of the six integration dimensions.

4. Findings and Discussion

Research findings from the conceptual analysis include the derived Integrated Lean 5.0 Framework, its KPIs, and the prescriptive Lean 5.0 tools, providing a non-speculative, normative integration.

4.1 Integrated Lean 5.0 Framework

The Integrated Lean 5.0 Framework, the central prescriptive outcome of this study, is presented in Figure 2 .
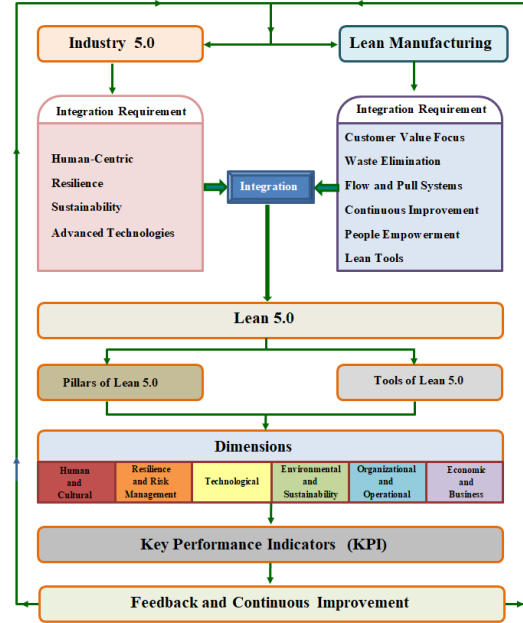
Figure 2. Proposed integration framework

It offers a multi-dimensional structure for aligning Lean Manufacturing with the normative pillars of Industry 5.0.

The framework's core elements—including Prerequisites, Integration Enablers, and Guiding Principles—support its structural deployment across the six Integration Dimensions. These dimensions serve as the comprehensive axes for evaluation and deployment, encompassing Technological, Human and Cultural, Organizational and Operational, Resilience, Environmental, and Economic factors.

4.2 Axiomatic Design Foundation

The Lean 5.0 framework is mathematically structured using principles from Axiomatic Design. This rigor is essential for building Resilient systems by ensuring the independence of functional requirements, which directly addresses the Industry 5.0 pillar, as shown in Eq. 1.

$$\{FR\} = A \,.\, \{DP\} \qquad (1)$$

The elements of the Design Matrix, A_{ij}, are the coupling coefficients, which define the relationship between the ith Functional Requirement and the jth Design Parameter as presented in Eq. 2.

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \qquad (2)$$

The mathematical goal of the Lean 5.0 parameter integration matrix methodology is to ensure the system satisfies the **independence axiom** (Axiom 1) by transforming the initial coupled design matrix (A) into a decoupled system. A decoupled matrix guarantees that a solution aimed at improving one pillar will not negatively impact another, thereby resolving inherent contradictions.

The Independence axiom requires that the design matrix A must be either diagonal or triangular. If the system is perfectly uncoupled, the matrix A is diagonal. A change in DP_i affects only FR_i. as given in Eq. 3.

$$A_{\text{uncoupled}} = \begin{pmatrix} A_{11} & 0 & .. & 0 \\ 0 & A_{22} & :: & 0 \\ .. & .. & .. & .. \\ 0 & 0 & .. & A_{nn} \end{pmatrix} \qquad (3)$$

Decoupled System (Acceptable, sequential dependence), If the system is decoupled, the matrix A is triangular. Changes can be made sequentially to DPs without undoing prior FR achievements, as shown in Eq.4.

$$A_{\text{dcoupled}} = \begin{pmatrix} A_{11} & A_{12} & .. & A_{1n} \\ 0 & A_{22} & :: & A_{2n} \\ .. & .. & :: & .. \\ 0 & 0 & .. & A_{nn} \end{pmatrix} \qquad (4)$$

The Lean 5.0 parameter integration matrix uses the discrete values $\{-1, 0, +1\}$ to model the A_{ij} coefficients. The methodology aims to eliminate all -1 coefficients (contradictions) and transform the final structure into the Decoupled form. This transformation is the mathematical guarantee that the proposed Lean 5.0 solution (DP_{new}) has maximized the Resilience of the system by ensuring all functional requirements can be satisfied independently.

4.3 Analysis of integration dimensions

Table 4 details the Human and Cultural Dimension, which redefines the human role by focusing on augmenting capabilities.

Table 4. *Key Aspects of Human-Centric Lean in Industry 5.0.*

Aspect	Description	Benefit
Augmented Decision Making	AI-driven, context-rich data	Enhances decision-making speed.
Skills Development	Continuous learning	Enables seamless transitions.
Human-Robot Collaboration	Teamwork and collaboration	Increases efficiency and safety
Ergonomic and Safe Design	User-friendly design	Enhances worker well-being.
Agility for Skill Adaption	Rapid shifts in skill requirements	Supports quick decision-making

Similarly, the Resilience, Business Continuity and Risk Management Dimension profoundly enhances the organization's capacity to anticipate and recover from disruptions by integrating predictive analytics and flexible operational strategies, with key strategies outlined in Table 5.

Table 5. *Strategies for Resilience in Lean-Industry 5.0.*

Aspect	Resilience Strategy	Impact
Supply Chain Disruptions	Real-time visibility; predictive analytics.	Reduces disruptions and downtime.
Skills Development	IoT integration; predictive maintenance	Minimizes unplanned outages
Equipment Failure	Agile approaches for demand shifts	Enhances responsiveness to market changes.
Quality Deviations	Continuous monitoring; root cause analysis.	Improves quality and reduces defects.

Table 6 details the key eco-efficient and sustainable practices within Lean-Industry 5.0, showcasing how advanced digital tools empower organizations to move beyond mere compliance.

Table 6. Sustainable Practices in Lean-Industry 5.0

Aspect	Sustainability Strategy	Benefit
Circular Economy	Closed-loop system, digital integration	Maximizes resource use and reuse
Product Life Cycle	Real-time design	Enhance resource efficiency
Energy Optimization	AI-optimized operations	Lower consumption and emissions.
Emissions and Waste Control	Continuous monitoring and improvement	Reduces waste and environmental impact

The Environmental and Sustainability Dimension outlines specific strategies for minimizing the ecological footprint and advancing circular economy practices, primarily driven by the framework's mandate to eliminate Carbon Muda. This approach proactively drives eco-innovations and realizes significant green benefits.

4.4 Multi-Dimensional Performance Indicator

To provide the necessary rigor and operational clarity, the framework introduces a set of multi-dimensional Key Performance Indicators, detailed in Table 7.

Table 7. Proposed KPIs for Lean-Industry 5.0 Integration.

KPI Category	Specific KPI	Metric
Human-centric	Workforce Engagement Index	Survey Scores
	Upskilling Rate	% new skills
Resilience	Supply Chain Resilience Index	Recovery Time
	System Downtime	Hours
Sustainability	Resource Consumption	KWH/Unit
	Throughput Rate	Products/Hour

These metrics are specifically formulated to evaluate the integration's effectiveness across the four critical facets: Economic, Environmental, Social (Human-Centric), and Operational. These KPIs reflect the simultaneous activation of both the foundational Lean Principles and the emerging Industry 5.0 Pillars across all six Integration Dimensions, including the Workforce Engagement Index (WEI), Supply Chain Resilience Index (SCRI), and Carbon Footprint Reduction.

4.5 Conceptualization of Lean 5.0 Tools

The conceptualization of Lean 5.0 Tools establishes the framework's practical novelty by defining explicit operational mechanisms and technological enablers that guarantee the achievement of the Industry 5.0 normative outcomes, moving beyond speculative technology labeling. The integration strategy is best illustrated through key tool mechanisms. Jidoka 5.0 integrates Explainable Artificial Intelligence (XAI), where the operational mechanism involves the XAI engine generating an immediate, human-readable root cause explanation upon halting production, ensuring the Human-Centric outcome.

Similarly, Value Stream Mapping 5.0 (VSM 5.0) utilizes a Real-time Digital Twin to extend mapping to include Social Value, Environmental Value, and Resilience/Risk Value layers. This mechanism allows the systematic assessment of material innovations (e.g., lightweight composites, bio-based feedstocks) within the Environmental Value layer, where the multidimensional environmental footprint (mass, volume, toxicity) is a key metric alongside traditional efficiency indicators like lead time. This allows simulation of process changes against all three Industry 5.0 pillars, ensuring integrated Sustainability. For asset management, Total Productive Maintenance 5.0 (TPM 5.0) employs Predictive Maintenance (PdM) algorithms coupled with Augmented Reality (AR) headsets. The mechanism provides operators with overlaid real-time diagnostics, facilitating the Human-Centric outcome and enhancing Resilience.

Other foundational tools are similarly re-conceptualized with prescriptive mechanisms: Poka-Yoke 5.0 uses computer vision and Augmented Reality for intelligent, predictive error-proofing, yielding a superior Augmented First-Pass Yield . Furthermore, Heijunka 5.0 and Kanban 5.0 leverage Artificial Intelligence/Machine Learning for dynamic adjustment of production buffers and schedules based on real-time data, establishing truly resilient and agile flow systems.

4.6 Illustrative Use Case

Poka-Yoke 5.0 integrates advanced digital technologies to transition from simple physical error-proofing to proactive, human-centered error prevention and system resilience. Consider a manual assembly station for high-value components where a critical error is using the incorrect torque sequence. In a Lean 4.0 system, error-proofing relies on a simple sensor or a physical jig. In contrast, Poka-Yoke 5.0 involves the operator wearing Augmented Reality glasses interlinked with Internet of Things-enabled torque tools and the cloud-based Digital Twin. The Augmented Reality system overlays the exact, real-time work instruction onto the physical component, highlighting the target fastener and the precise torque value. If the operator attempts to use the tool out of sequence or applies the wrong torque, the system instantly generates a highly visible, auditory alert in the operator's field of view. Simultaneously, this attempted error is logged into the Digital Twin, which immediately analyzes the data to identify systemic process drift or potential machine calibration issues, thereby enhancing Resilience by predicting and correcting the root cause of the error before component damage occurs.

5. Empirical Case Study

The validation was executed in a large-scale additive manufacturing facility, a sector characterized by high-value, complex batches. The data for this case study were drawn from the research presented in reference [55]. The existing Lean 4.0 system, optimized for speed, exhibited a critical design contradiction: The necessity to maximize Throughput through high automation conflicted with the demand for full human override capability. This represented an initial coupled matrix where $A_{ij} = -1$. Allowing operators full manual control for custom setups caused the setup error rate to soar to 3.1%, resulting in massive material scrap and frequent system downtime.

The Lean 5.0 parameter integration matrix was applied to model and resolve the negative coupling coefficient ($A_{ij} = -1$) between the DP of Automation Level and the FR of Human Override Authority. The inventive solution, driven by the framework, involved integrating a Jidoka 5.0 system: First is the Explainable AI can be a vision model confirms setup integrity automatically. The second is the Augmented Override Module The Human Override Module is always available, but XAI provides immediate, transparent diagnostic feedback, enabling the human

operator to intervene effectively and accurately, thereby decoupling the two functional requirements.

The following four formalized metrics were used to quantitatively compare the Baseline (Lean 4.0) and the Lean 5.0 parameter integration matrix solution over the observation period T.

The results summarized in Table 8 confirm that the Lean 5.0 parameter integration matrix solution successfully achieved the required decoupling, leading to massive gains in Industry 5.0 pillars while maintaining or slightly increasing Lean efficiency.

Table 8. Lean 5.0 Comparative Performance Metrics

Key Metric	Baseline	Lean 5.0
Operational Efficiency	100%	100%
System Resilience	18.5 minutes	4.2 minutes
Setup Error Rate	3.1%	0.8%
Material Scrap Rate	0.75%	0.2%

The empirical results conclusively validate the prescriptive power of the Lean 5.0 parameter integration matrix methodology in resolving design contradictions and achieving the multidimensional goals of Lean 5.0. The quantitative comparison between the Lean 4.0 Baseline and the Lean 5.0 parameter integration matrix Solution across all relevant metrics directly addresses the need for empirical proof of concept. The core finding is that the implementation of the Jidoka 5.0/XAI solution successfully decoupled the conflicting functional requirements The original Lean 4.0 system exhibited a negative coupling coefficient ($A_{ij} = -1$) where increasing human authority negatively impacted throughput and quality. By leveraging XAI, the new design ensures that Human Override Capability is maintained and Setup Error Rate is drastically reduced. This outcome demonstrates that the inventive solution satisfied the Independence Axiom; the design now allows for the improvement of the human factor without degradation of the Lean factors, proving the framework's ability to transition from a coupled to a decoupled design matrix.

Throughput Rate Index confirms that the significant gains in the Industry 5.0 pillars were achieved not at the expense of traditional Lean goals, but while slightly enhancing them. This validates the core tenet of Lean 5.0 that efficiency and human-centric needs are not a trade-off.

The 77% reduction in Mean Time to Recovery is the most significant validation of the Resilience pillar. This result is a direct measure of the system's ability to autonomously diagnose and quickly recover from sensor and system failures, ensuring minimal production disruption.

The 74% reduction confirms the success of the human-centric design. By providing the operator with transparent, immediate diagnostic feedback via XAI, the system prevents the operator from making the error in the first place, effectively transforming complex manual intervention from a vulnerability into a dependable, guided process.

The 73.3% reduction directly demonstrates the framework's measurable impact on the sustainability pillar by minimizing waste in the production of high-value additive manufacturing parts.

6. Analysis and Insights

An analysis of Lean-Industry 5.0 integration findings details the proposed framework's theoretical and practical implications

6.1 Critical Analysis

The proposed Integrated Lean 5.0 Framework advances the existing body of knowledge by transitioning the discussion from a purely technological synthesis to a prescriptive, normative integration. The critical contribution lies in the systematic derivation of the six Integration Dimensions, which collectively form the analytical lens guaranteeing Industry 5.0 compliance. Unlike previous descriptive models, this framework mandates that performance be rigorously balanced across all six axes—including non-traditional ones like the Human and Environmental Dimensions—to achieve true Industry 5.0 outcomes.

The framework operationalizes novelty through two key analytical constructs. First, the Lean 5.0 Tools are defined by unique, prescriptive mechanisms that explicitly assure an Industry 5.0 outcome. For instance, Jidoka 5.0 integrates Explainable AI to enhance human trust and instant upskilling, a necessary step beyond the simple automation of the 'stop' function found in Lean 4.0. Second, the introduction of Carbon Muda structurally formalizes environmental impact within the Lean value stream as the systematic identification and elimination of waste associated with greenhouse gas emissions and resource depletion throughout the product lifecycle.

The framework integrates this concept into VSM 5.0 via the Digital Twin, thereby providing a necessary analytical bridge between the waste elimination principle and the pillar of Sustainability.

6.2 Managerial Implications

The framework provides clear, actionable guidance for industry leaders transitioning to Industry 5.0. Investment justification must move beyond simple Return on Investment and throughput. Leaders must evaluate proposed technologies based on their verifiable contribution to the Multi-Dimensional KPIs, ensuring value creation across Economic, Environmental, and Social factors simultaneously. The primary focus of technological adoption must be human augmentation, not replacement. Managerial practices should shift to emphasize cross-training via AR/VR and decentralized decision-making, transforming operators into augmented, proactive problem-solvers who drive Kaizen cycles.

6.3 Critical Discussion

While the framework provides significant theoretical grounding and operational clarity, its purely conceptual nature is acknowledged. The true challenge lies in empirical validation, which requires developing standardized metrics for non-traditional areas, such as the social value layers within VSM 5.0. Future research must, therefore, focus on developing industry-specific use cases and simulation models to confirm the proposed synergistic relationships and rigorously quantify the improved performance against the new Industry 5.0 KPIs.

7. Conclusion

To sum up, this study addressed a critical theoretical and practical gap by proposing a novel, multidimensional conceptual framework that systematically integrates the operational efficiency of Lean Manufacturing with the normative goals of Industry 5.0. The primary theoretical contribution is the establishment of the Lean 5.0 paradigm, which moves beyond Lean 4.0 by providing the necessary structure and prescriptive mechanisms to guarantee human-centric, resilience, and sustainability value creation. The framework's contribution is substantiated by the systematic derivation of the six Integration Dimensions that serve as the validated axes for holistic Industry 5.0 implementation. This foundation, grounded in the universal principles of the Axiomatic Design methodology, inherently makes the

framework sector-agnostic—it adapts by redefining the sector-specific Functional Requirements and Design Parameters without changing its core structure. Furthermore, the conceptualization of Lean 5.0 Tools provides specific operational mechanisms that guarantee the achievement of Industry 5.0 pillars. The introduction of Carbon Muda and the detailed, multi-dimensional key performance indicators further establish the analytical rigor required to measure this holistic alignment. The framework's effectiveness is substantiated by an empirical case study in an additive manufacturing environment. The quantitative comparison provided demonstrates that implementing the Lean 5.0 parameter integration matrix successfully resolved the conflict between efficiency and human-centric goals, offering tangible improvements in operational performance, Resilience, and Sustainability metrics compared to the Lean 4.0 baseline. This work provides the prescriptive foundation necessary for organizations to align their production practices with the complex demands of the evolving industrial landscape, thereby advancing the field of cognitive manufacturing.

A key limitation of this research lies in its reliance on a single case study; therefore, future work must focus on sector-specific validation across diverse industrial contexts to confirm broader applicability. This is essential, particularly when considering the constraints of advanced tools like Value Stream Mapping 5.0 Digital Twins, which introduce inherent limitations related to data accuracy and a substantial computational burden. To solidify the framework, research must prioritize algorithmic development for predictive mechanisms such as Jidoka 5.0 and Total Productive Maintenance 5.0, alongside large-scale data collection to establish benchmarks and validate the operational feasibility of multi-dimensional Key Performance Indicators. Furthermore, to enhance adoption, a modular and tiered Lean 5.0 Parameter Integration Matrix roadmap is required for Small and Medium-sized Enterprises, detailing prioritized initial investments based on enterprise maturity and conflicting goals, ensuring the framework is scalable and accessible even with limited access to advanced technologies. Finally, future investigation must address critical human factors by studying how to mitigate workforce resistance through training and feedback mechanisms, while simultaneously ensuring the fair deployment of Artificial Intelligence-driven Lean 5.0 tools is governed by a robust ethical Artificial Intelligence governance framework that guarantees transparency and non-bias across various segments of modern manufacturing.

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