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HUMAN FACTORS IN LEAN MANUFACTURING: A CHRONOLOGICAL REVIEW

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Abstract:

Human factors are increasingly recognized as a critical determinant of success in lean manufacturing systems; however, existing studies remain fragmented across different periods and research focuses. This study provides a structured understanding by conducting a chronological literature review of human factors in lean manufacturing. A systematic search was performed using the Scopus database with the keywords "human factor" and "lean manufacturing," applying strict inclusion criteria. From 395 initial records, 113 journal articles were selected for analysis. The literature was categorized into four temporal phases: Emergent (2003–2012), Development and Recognition (2013–2017), Expansion and Peak Interest (2018–2020), and Consolidation and Stabilization (2021–2026). The findings indicate a clear evolution from basic awareness of human-related issues to a stronger emphasis on ergonomics, organizational culture, and workforce engagement. Recent studies highlight the integration of human factors with performance measurement, digitalization, and Lean Six Sigma practices, alongside

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growing alignment with Industry 4.0 and Industry 5.0. Overall, human factors have evolved from a supporting role to a central element in lean system design. This study offers a temporal framework that enhances understanding of research trends and informs future human-centric lean manufacturing research.

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Human Factors, Industry 5.0, Lean Manufacturing, Review

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Introduction

Human factors are increasingly recognized as a cornerstone in the effective implementation and sustainability of lean manufacturing systems. While lean manufacturing originated as a set of technical tools and process optimization strategies aimed at eliminating waste and improving efficiency, its long-term success is fundamentally dependent on the people who operate, manage, and continuously improve these systems. Research highlights that employee involvement, training, leadership commitment, organizational culture, and ergonomic considerations are not just supportive elements but critical drivers of lean outcomes. For example, studies show that human factors such as employee engagement, leadership competency, and continuous training significantly influence the adoption and performance of lean practices in both large-scale industries and small- to medium-sized enterprises (SMEs) (Bento & Tontini, 2024; Eriksson et al., 2024; Hines et al., 2025; Qureshi et al., 2025). Moreover, integrating human-centric approaches—such as participative decision-making, empowerment, and attention to well-being—can enhance operational performance while mitigating risks like work intensification or resistance to change (Bento & Tontini, 2024; Ferrazzi et al., 2025; Gamage et al., 2025; Jesus et al., 2024; Yilmaz, 2025).

The evolution toward Industry 4.0 and now Industry 5.0 further amplifies the importance of human factors in lean manufacturing. As digital technologies such as artificial intelligence (AI), Internet of Things (IoT), and advanced automation become embedded within production systems, there is a growing need to balance technological advancements with human strengths—creativity, adaptability, problem-solving, and collaboration (Eriksson et al., 2024; Hines et al., 2025; Stanisavljev et al., 2025; G. Tortorella et al., 2024). Recent research underscores that successful lean transformations require a holistic approach: aligning technical innovations with organizational culture, leadership behaviors that foster trust and empowerment, robust communication channels, and ergonomic workplace design (Brunner,

Siebenbürger, et al., 2024; Brunner, Yuching, et al., 2024; Gatell & Avella, 2024; Wodajeneh et al., 2024). Neglecting these human dimensions can lead to suboptimal results or even failure of lean initiatives. Therefore, understanding and integrating human factors is essential for achieving not only productivity gains but also sustainable competitiveness and resilience in modern manufacturing environments (Bento & Tontini, 2024; Eriksson et al., 2024; Ferrazzi et al., 2025; Hines et al., 2025; Qureshi et al., 2025).

Literature Review

Therefore, understanding and integrating human factors is essential for achieving not Human factors play a pivotal role in the successful implementation and sustainability of lean manufacturing systems. Lean manufacturing, originally developed in Japan, emphasizes waste reduction, efficiency, and continuous improvement. However, its success is not solely dependent on technical tools but also on the integration of human-centric approaches. Research highlights that the neglect of human factors, such as worker well-being, ergonomic conditions, and organizational culture, can hinder the effectiveness of lean practices and negatively impact employee satisfaction and productivity (Harikrishnan & Annamalai, 2022; Srinivasa Rao & Niraj, 2016a). For instance, ergonomic considerations, such as optimizing workstations and reducing physical strain, have been shown to improve both worker health and production rates (Colim et al., 2021; Nunes & Machado, 2007; Srinivasa Rao & Niraj, 2016b).

The integration of human factors into lean manufacturing often involves addressing challenges such as employee training, motivation, and organizational culture. Studies suggest that a comprehensive approach combining technical, human, and organizational elements is essential for a sustainable lean transformation (Ayough & Farhadi, 2019; Khan & Dalu, 2019). For example, frameworks that incorporate human behavioral factors, such as learning and motivation, alongside technical processes, have been shown to enhance productivity and foster a culture of continuous improvement (Ayough & Farhadi, 2019; Costa et al., 2019). Additionally, the role of top management in fostering effective communication, providing training, and supporting Kaizen events is critical for engaging the workforce and achieving long-term success (Costa et al., 2019).

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Ergonomics and human-robot collaboration (HRC) are emerging as key areas of focus within lean manufacturing. Collaborative robotic workstations, designed with ergonomic principles, have demonstrated significant improvements in worker well-being, task efficiency, and error reduction (Colim et al., 2021; Poetters & Sen, 2025). These systems not only enhance productivity but also address repetitive strain and cognitive load, making them particularly valuable in monotonous or physically demanding tasks (Caiazzo et al., 2022; Colim et al., 2021). Furthermore, the integration of Industry 4.0 technologies, such as sensors and simulation tools, supports the design of human-centered lean systems, enabling better decision-making and process optimization (Marinelli, 2022; Nunes & Machado, 2007).

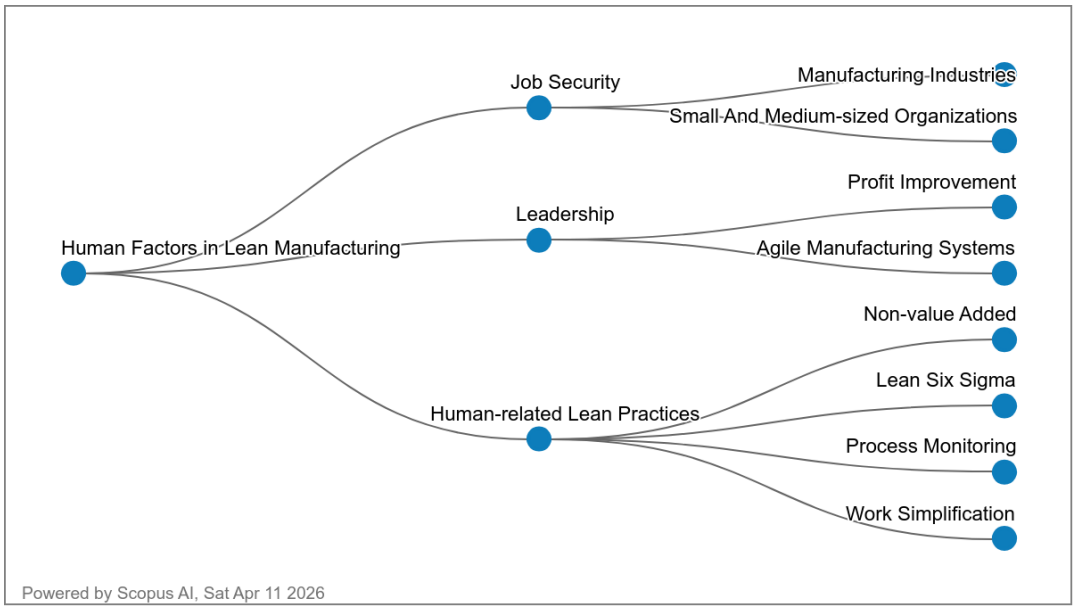


Figure 1: Literature Concept Map Framework

Finally, the social sustainability of lean manufacturing is increasingly recognized as a critical factor. Practices such as standardized work, multifunctional teams, and decentralized decision-making have been shown to improve worker satisfaction and organizational responsibility, particularly in labor-intensive industries (Díaz Reza et al., 2026). By prioritizing human factors, lean manufacturing can achieve not only operational efficiency but also a more sustainable and inclusive work environment. This holistic approach underscores the importance of aligning technical innovations with human-centric strategies to ensure the long-term success of lean initiatives (Díaz Reza et al., 2026; Harikrishnan & Annamalai, 2022).

Methods

Data Collection

Section Human factors have progressively emerged as a critical dimension in the evolution of lean manufacturing, shifting the paradigm from a predominantly tool- and process-centric philosophy toward a more integrated socio-technical perspective that emphasizes the role of human capabilities, behaviors, and organizational culture in achieving sustainable operational excellence. While early lean implementations focused heavily on waste elimination and efficiency optimization, contemporary research underscores that the success and longevity of lean systems are inherently dependent on workforce engagement, ergonomic design, leadership

practices, and human resource management strategies. In response to this intellectual transition, the present chronological review systematically maps the development of human factors within lean manufacturing literature, capturing how scholarly attention has evolved across different periods, themes, and methodological approaches. To ensure a robust and transparent evidence base, this study employed a single-step data collection process using the Scopus database, widely recognized for its comprehensive coverage of peer-reviewed journals and high-quality academic publications. The data collection procedure involved the formulation of precise keyword strings related to "human factors" and "lean manufacturing," followed by the application of inclusion and exclusion criteria to filter relevant articles based on subject area, document type, language, and publication quality. The resulting dataset represents a curated body of literature that reflects both foundational contributions and emerging trends in the field. The adoption of a rigorous and systematic data collection strategy is essential for enhancing the reliability and validity of the review, as it minimizes selection bias, ensures replicability, and strengthens the credibility of the findings. Moreover, such methodological rigor enables meaningful longitudinal analysis, allowing for the accurate interpretation of thematic shifts and research trajectories over time. By establishing a consistent and transparent data collection framework, this study not only provides a reliable synthesis of existing knowledge but also offers a solid foundation for identifying research gaps and future directions in the integration of human factors within lean manufacturing systems.

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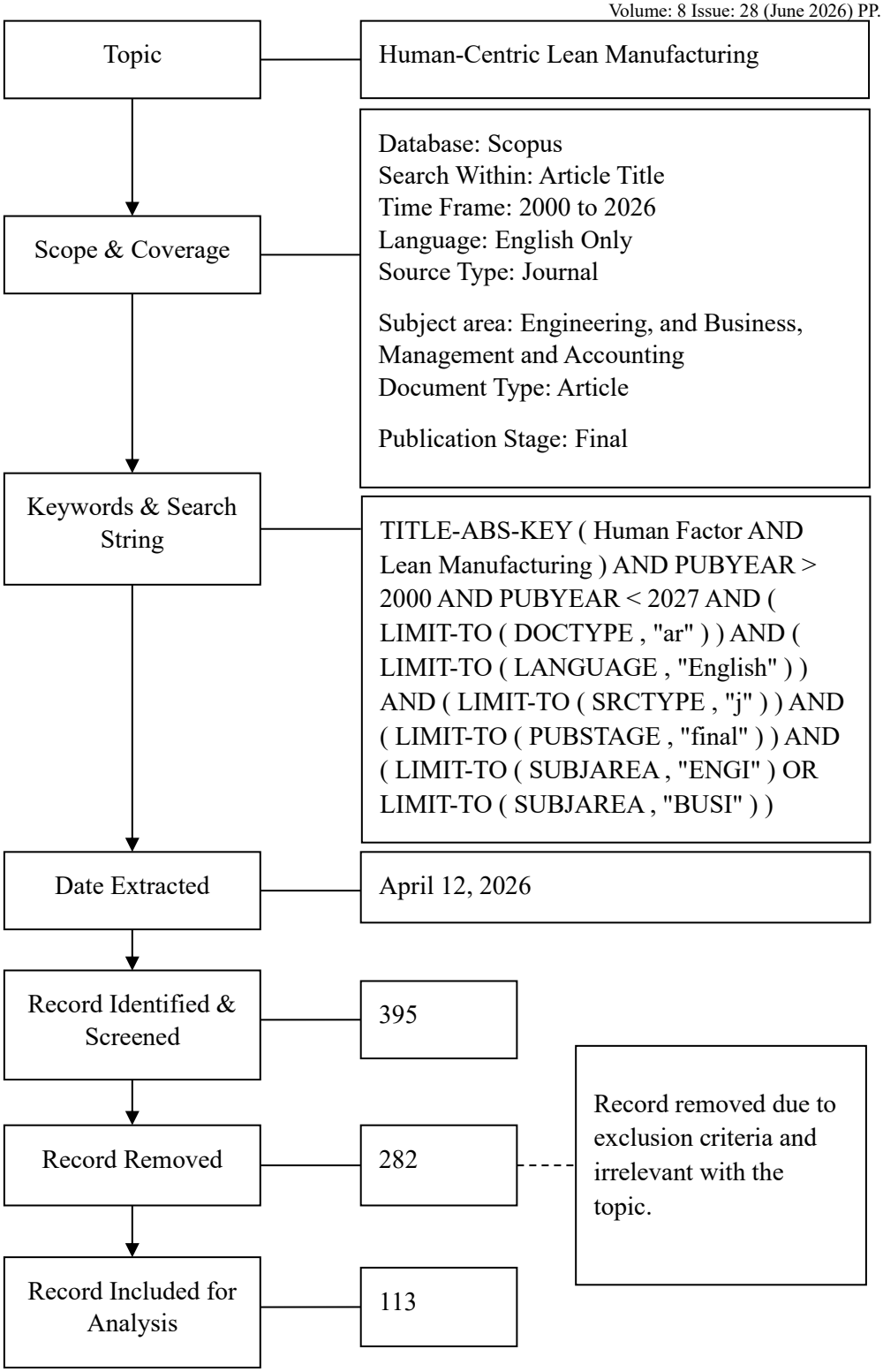


Figure 2: Flow Diagram of The Search Strategy.

Source: (Moher et al., 2009)

A structured literature identification and screening strategy was applied using the Scopus database to ensure breadth, quality, and disciplinary relevance in reviewing human factors in lean manufacturing. The search string, TITLE-ABS-KEY (Human Factor AND Lean

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Manufacturing), was designed to capture studies in which the core concepts appeared in the title, abstract, or author keywords, thereby improving retrieval sensitivity and reducing the risk of omitting conceptually relevant articles. The search was further constrained to publications from 2000 to 2026 to reflect the modern evolution of lean manufacturing scholarship, particularly its shift from a predominantly technical production philosophy toward a more socio-technical and human-centred perspective. Additional filters were imposed to strengthen methodological rigor and academic credibility, including English language only, journal source type, final publication stage, and article document type, while restricting subject areas to Engineering and Business, Management and Accounting ensured direct alignment with both the operational and organizational dimensions of lean implementation. This search process initially identified 395 records, indicating substantial scholarly attention to the topic; however, after systematic screening, 282 records were excluded due to issues such as duplication, limited relevance, conceptual mismatch, non-empirical focus, or insufficient engagement with human-factor dimensions in lean contexts. The final inclusion of 113 articles demonstrates a deliberate balance between comprehensiveness and specificity, yielding a focused and high-quality evidence base for analysis. Such a screening outcome is methodologically justified because it reflects the removal of peripheral literature while preserving studies that meaningfully address the intersection of human factors and lean manufacturing, thereby enhancing the review's validity, thematic coherence, and potential contribution to high-impact scholarly discourse.

Data Clustering

In a chronological review of Human Factors in Lean Manufacturing, the clustering of publication data into meaningful temporal phases constitutes a critical analytical step for uncovering the intellectual evolution and research dynamics of the field. Given that the dataset was systematically retrieved from a reputable and comprehensive source such as Scopus using well-defined keywords and advanced search strategies, the resulting publication records provide a reliable basis for longitudinal trend analysis. However, raw annual counts alone offer limited interpretive value unless they are structured into coherent groupings that reflect shifts in research intensity and thematic development. By organizing the data according to publication year and volume, clustering enables the identification of distinct phases—such as emergence, growth, maturity, and consolidation—thereby revealing patterns that correspond to changes in scholarly attention, technological advancements, and industrial priorities. This approach enhances interpretability by transforming discrete data points into analytically meaningful segments, allowing researchers to contextualize fluctuations in output, detect periods of rapid expansion or stagnation, and relate these trends to broader developments in lean manufacturing and human-centric systems. Consequently, temporal clustering not only strengthens the rigor of the review but also facilitates a more nuanced understanding of how the field has progressed over time, providing a structured foundation for subsequent thematic and theoretical analysis.

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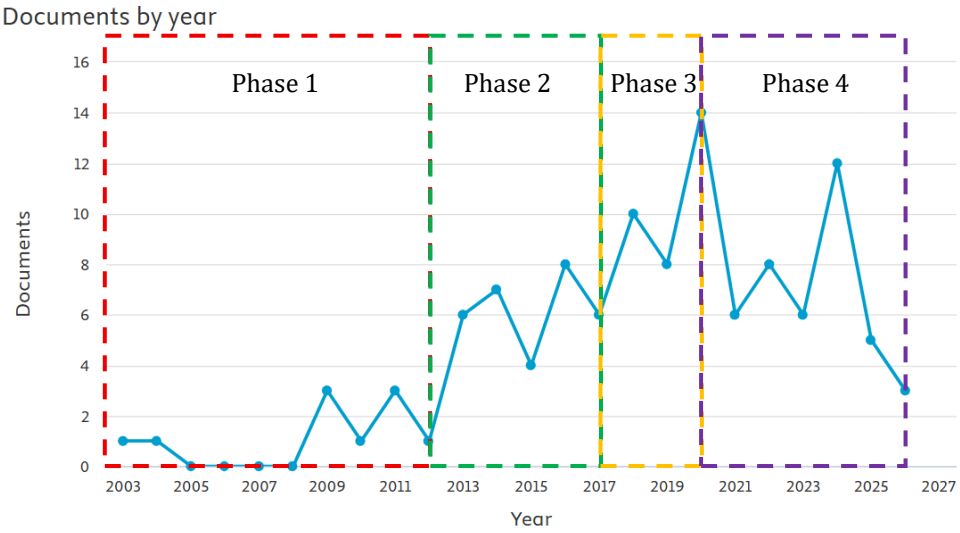


Figure 3: Number of Documents Per Year

Phase 1: Emergent Stage (2003–2012)

This phase represents the nascent stage of research, characterized by limited and irregular scholarly attention. The low publication frequency suggests that human factors were not yet a central theme within lean manufacturing discourse, which during this period remained predominantly focused on technical efficiency, waste reduction, and process optimization. The few studies published were likely exploratory, conceptual, or peripheral, laying the groundwork for integrating human-centric considerations such as ergonomics, worker involvement, and organizational behavior into lean systems. The gaps between publication years further indicate a lack of sustained research momentum, justifying its classification as an early emergence phase.

Phase 2: Development and Recognition Stage (2013–2017)

This period marks a transition toward increased recognition of human factors as a critical component in lean implementation. The noticeable rise in publications—from 6 in 2013 to 8 in 2016—reflects growing academic and industrial awareness that lean success depends not only on tools but also on human capabilities, culture, and engagement. Research during this stage likely began to incorporate interdisciplinary perspectives, including human resource management, safety, and socio-technical systems. The relatively stable upward trend indicates consolidation of interest and the beginning of a more structured research stream.

Phase 3: Expansion and Peak Interest Stage (2018–2020)

This phase represents a significant expansion and peak in research activity, culminating in the highest recorded output in 2020 (14 publications). The sharp increase suggests that human factors became a central theme in lean manufacturing research, driven by broader trends such as Industry 4.0, digital transformation, and the need for human–technology integration. Scholars increasingly examined topics such as employee empowerment, cognitive ergonomics, safety culture, and workforce adaptability. The peak in 2020 indicates a mature and highly

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active research domain, where human-centric approaches are no longer supplementary but essential to lean system performance.

Phase 4: Consolidation and Stabilization Stage (2021–2026)

Following the peak, this phase reflects a period of consolidation and thematic refinement. Although publication counts fluctuate, the overall output remains relatively strong, indicating sustained scholarly interest. The variability may be attributed to shifts in research focus, including integration with emerging paradigms such as Lean 5.0, human–AI collaboration, and sustainability. Rather than rapid growth, this stage emphasizes depth, methodological rigor, and theoretical advancement. The slight decline toward 2025–2026 may also reflect publication lag or the natural stabilization of a mature research field. This phase confirms that human factors are now an embedded and indispensable dimension of lean manufacturing research.

Result & Discussion

Emergent Stage (2003–2012)

The findings and discussion of Phase 1 indicate that early research on human factors in lean manufacturing remained closely aligned with operational performance yet progressively revealed the embedded role of organizational and human dimensions. A chronological structuring into three sub-periods—foundation (2003–2004), broadening (2009–2010), and integration (2011–2012)—provides analytical clarity. This classification reflects an initially discontinuous publication pattern, followed by increased scholarly attention post-2009 and a gradual diversification of methodological approaches alongside clearer socio-technical perspectives.

In the foundation period (2003–2004), studies established that lean manufacturing cannot be interpreted purely through technical practices. (Shah & Ward, 2003) demonstrated that contextual factors, particularly plant size, significantly influenced lean implementation, while validating four interrelated lean bundles: just-in-time (JIT), total quality management (TQM), total productive maintenance (TPM), and human resource management (HRM). These bundles collectively explained a substantial proportion of operational performance variation, positioning HRM as a core structural component rather than a supporting function. Complementarily, (Seppälä & Klemola, 2004) shifted attention toward employee experience, examining job satisfaction, stress, and perceived work conditions under lean environments. Together, these studies laid the conceptual foundation by linking lean systems with organizational context and employee well-being.

The broadening period (2009–2010) reflects expansion in empirical scope and conceptual depth.(Gebauer et al., 2009) extended lean analysis into the pharmaceutical sector, confirming that practices such as TPM, JIT, TQM, and HRM positively influenced operational performance in regulated environments. This reinforced the generalizability of lean while highlighting HRM as a performance-enabling mechanism. (Farris et al., 2009) further emphasized employee development through Kaizen events, identifying key factors influencing attitudinal outcomes and problem-solving capability. This marked a shift toward behavioural and learning dimensions of lean. At the same time, (Benders & Slomp, 2009) introduced a critical perspective, arguing that organizational tools and concepts may generate implementation challenges, thereby requiring reflective adaptation rather than direct transfer.

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(Smith, 2010) broadened the context to service organizations, demonstrating that lean principles interact with multiple functional domains, including human resources and finance. Collectively, this phase shows a transition toward broader sectoral application, human development, and critical organizational insight.

The integration period (2011–2012) demonstrates a more mature socio-technical understanding. (Marksberry et al., 2011) showed that lean success, particularly in Toyota's production levelling, depends on coordination across departments supported by HR policies. (Glover et al., 2011) examined the sustainability of human outcomes from Kaizen initiatives, identifying factors influencing long-term employee commitment. (Taj & Morosan, 2011) through a multi-plant study in China, confirmed that human resources are central to shaping lean performance, with sectoral differences reflecting varying levels of capability and maturity. (Stone, 2012) contributed a critical methodological perspective by highlighting limitations in lean measurement reliability and emphasizing organizational development and human resource principles in sustaining transformation.

Across Phase 1, several patterns emerge. First, human factors evolved from implicit contextual elements to explicit constructs involving employee attitudes, engagement, and cooperation. Second, methodological approaches became more diverse, incorporating case studies, field research, and statistical analysis. Third, the research focus shifted from assessing performance outcomes to understanding the conditions for sustainable lean implementation. Overall, the findings consistently indicate that lean manufacturing is inherently socio-technical, where operational performance is mediated by human capabilities, organizational systems, and cross-functional integration. These insights confirm that human factors were foundational, rather than peripheral, in shaping early lean manufacturing research

Development and Recognition Stage (2013–2017))

The findings from Phase 2 (2013–2017) demonstrate a clear transition in lean manufacturing research, where human factors evolved from supportive elements into central determinants of implementation success, sustainability, and organizational performance. This stage can be structured into three chronological clusters—early recognition (2013), system expansion (2014–2015), and consolidation (2016–2017)—reflecting progressive theoretical development and empirical strengthening. The 2013 studies emphasized the growing importance of people and culture, the 2014–2015 studies expanded into structured human resource and organizational frameworks, while the 2016–2017 studies provided robust empirical validation across diverse contexts.

In the early recognition period (2013), research began to explicitly foreground the role of human and organizational elements in lean systems. (Glover et al., 2013) identified that although kaizen programs delivered operational benefits, human resource outcomes were insufficiently measured, raising concerns regarding sustainability. (Gupta et al., 2013) further demonstrated that organizational culture and HRM are key enablers of change, while financial capacity indirectly influences lean through management commitment. Expanding the scope, (Gnoni et al., 2013) integrated lean principles with occupational safety systems, linking productivity with proactive risk management. Similarly, (Schwagerman III & Ulmer, 2013) emphasized that Toyota's success is rooted not only in tools but in employee-driven learning culture and problem-solving practices. Empirical validation by (Yang & Yang, 2013) confirmed

that lean performance improves when technical practices are integrated with HRM and people-related factors. Collectively, these studies marked a shift from technical emphasis toward recognizing human capability, learning behaviour, and cultural alignment as essential components of lean implementation.

The system expansion period (2014–2015) reflects a broader and more structured treatment of human factors within lean systems. (Agarwal et al., 2014) found that managerial capability, education, and firm characteristics significantly influence the adoption of lean practices, indicating that human capital plays a strategic role.(Gošnik et al., 2014) identified lack of human resources as a key barrier to Lean Six Sigma, while (James & Jones, 2014) highlighted the importance of adapting lean practices to socio-cultural contexts. (G. L. Tortorella & Fogliatto, 2014) advanced the field by proposing structured methods to assess HRM and organizational learning, moving beyond conceptual discussions toward diagnostic tools. In 2015, (Douglas et al., 2015) confirmed that management involvement is a critical success factor, while (Mamat et al., 2015) emphasized the role of soft practices such as communication and employee attitude in Malaysian SMEs. Ergonomic considerations were also reinforced by (Bartnicka, 2015), who demonstrated their importance in improving working conditions. Overall, this period expanded the human factor discourse into structured HRM systems, organizational learning, and context-sensitive implementation strategies.

The consolidation period (2016–2017) presents stronger empirical evidence and methodological rigor, confirming human factors as integral to lean systems. (Liang et al., 2016) demonstrated that lean principles improve coordination and outcomes in healthcare, while (Srinivasan et al., 2016) showed that 5S implementation enhances safety climate, particularly management commitment and involvement. (H. van Dun & Wilderom, 2016) linked leadership values with team effectiveness, highlighting the role of behavioural factors in lean success. Similarly, (Shokri et al., 2016) identified organizational culture, education, and continuous improvement vision as key readiness factors. Ergonomic challenges were further examined by (Da Silva et al., 2016), who revealed mismatches between work demands and worker capabilities. By 2017, studies such as (Minh et al., 2017) and (Ainul Azyan et al., 2017) emphasized training, communication, and leadership commitment as critical success factors, while (Botti et al., 2017) demonstrated that ergonomics must be integrated into production system design. These findings confirm that human factors—including leadership, communication, ergonomics, and participation—are fundamental determinants of lean effectiveness across sectors.

Across the entire 2013–2017 period, several patterns emerge. First, the research focus shifted from recognizing human factors to systematically measuring and analysing their impact. Second, methodological approaches became more diverse, incorporating quantitative models, case studies, and mixed methods. Third, the application scope expanded across industries and geographical contexts, indicating broader relevance. Finally, a consistent finding is that technical tools alone are insufficient; instead, management commitment, training, cultural alignment, and employee involvement repeatedly emerge as critical drivers of lean success.

In summary, Phase 2 represents the development and recognition stage in which human factors became an established domain within lean manufacturing research. The progression from early recognition to empirical consolidation demonstrates that people-related variables are not peripheral, but essential for achieving sustainable and effective lean implementation.

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Expansion and Peak Interest Stage (2018–2020)

The findings from Phase 3 (2018–2020) demonstrate a significant expansion and maturation of research on human factors in lean manufacturing, where the human dimension evolved from a supporting role into a central strategic and operational concern. This stage can be systematically clustered into three sub-periods—expansion (2018), peak development (2019), and diversification and consolidation (2020)—reflecting progressive thematic depth and methodological sophistication. The 2018 studies emphasized readiness, culture, and assessment; 2019 deepened integration with system design and continuous improvement; while 2020 exhibited the widest thematic spread, linking human factors to performance, sustainability, ergonomics, and resilience.

In the expansion phase (2018), the literature formalized the human dimension through structured frameworks, cross-national perspectives, and measurement tools. (Viddy et al., 2018) highlighted the role of human judgment in strategic decision-making under uncertainty, particularly in selecting between lean, agile, and hybrid supply chain configurations. (Oliveira et al., 2018) positioned human resource management (HRM) as a structural pillar within world-class manufacturing systems, reinforcing its strategic importance. (De Vries & Van der Poll, 2018) emphasized self-directed teams, leadership behaviour, and participation as essential to lean maturity, while (Garza-Reyes et al., 2018) identified human readiness, leadership, and organizational preparedness as critical gaps in regulated industries. Similarly, (Virmani et al., 2018) classified HRM as a causal success factor in leagile systems. Notably,(Neumann et al., 2018) introduced an important ergonomic perspective, demonstrating that lean-driven process improvements could increase injury risks if human limitations are neglected. Cultural alignment was further explored by (Taherimashhadi & Ribas, 2018) and (DeSanctis et al., 2018), who showed that organizational and national culture significantly influence lean success. Collectively, these studies indicate a shift toward recognizing human, cultural, and ergonomic dimensions as prerequisites for effective lean implementation.

The peak development phase (2019) reflects deeper integration of human factors into lean system design and continuous improvement. (Lamon et al., 2019) demonstrated that human-robot collaboration can be optimized by aligning tasks with worker capabilities, marking a transition toward technologically embedded human factors. (Costa et al., 2019) identified workforce engagement, communication, and training as key drivers of sustainable continuous improvement, positioning human factors as foundational rather than supportive. (Pimentel et al., 2019) reported improvements in both productivity and worker self-esteem following cellular transformation, while (Ayough & Farhadi, 2019) integrated behavioural constructs such as learning and motivation into lean system models. In non-traditional contexts,(Jain & Ajmera, 2019) confirmed the importance of human and organizational factors in healthcare lean applications, while (Vukadinovic et al., 2019) emphasized early human resource development and competency building. These contributions illustrate a peak in conceptual richness, where human, technical, and organizational elements are treated as interdependent components of lean performance systems.

The diversification and consolidation phase (2020) presents the strongest evidence of human factors as a core dimension of lean performance and sustainability. (Abdallah, 2020) found that leadership, training, and employee inclusion are critical in healthcare lean implementation, highlighting the importance of professional engagement. (Hernandez-Matias et al., 2020)

demonstrated that human-related practices such as empowerment and cultural support directly influence operational outcomes, forming a causal chain from human engagement to performance improvement. Ergonomic concerns were reinforced by (Nallusamy et al., 2020), who linked musculoskeletal issues to poor workplace design, emphasizing the need for human-centered redesign. At a strategic level, (Kolos, 2020) argued that human flow should be prioritized within value streams, while (Zhu & Zhang, 2020) highlighted personnel integration as essential for lean-green sustainability. Additionally, (Basu et al., 2020) showed that external volatility can moderate lean-performance relationships, indicating that human and technical capabilities alone are insufficient without contextual stability. These findings confirm that human factors are embedded across operational, strategic, and environmental dimensions of lean systems.

Across the entire Phase 3 period, several patterns emerge. First, human factors evolved into strategic drivers of performance, innovation, and sustainability. Second, methodological approaches diversified significantly, incorporating advanced quantitative models, mixed methods, and optimization techniques. Third, the application scope expanded beyond manufacturing into healthcare, construction, and supply chains. Finally, while human factors consistently enhance lean outcomes, several studies caution that neglecting ergonomics and worker well-being may lead to unintended negative consequences.

In summary, Phase 3 represents a critical turning point in which human factors became fully embedded within lean manufacturing discourse. The progression from readiness and cultural alignment (2018) to integrated system design and capability development (2019), and finally to performance, sustainability, and contextual resilience (2020), demonstrates that human factors are now fundamental to explaining lean success and long-term organizational effectiveness.

Consolidation and Stabilization Stage (2021–2026)

The findings from Phase 4 (2021–2026) demonstrate that research on human factors in lean manufacturing has reached a stage of consolidation, integration, and conceptual maturity. Unlike earlier phases that primarily established the importance of people-related variables, this stage reflects a stable recognition that human factors are inseparable from lean maturity, digital transformation, ergonomics, sustainability, and long-term organizational performance. The literature can be structured into three chronological clusters—consolidation (2021–2022), system integration (2023–2024), and human-centered maturity (2025–2026)—each reflecting increasing depth and integration of human-centric perspectives.

In the consolidation phase (2021–2022), empirical evidence consistently confirms that human factors are no longer peripheral but central to lean performance and organizational stability. (Gilbert & Teglborg, 2021) showed that digital transformation and employee empowerment can coexist, suggesting that technological advancement does not diminish human agency when supported by effective HR practices. (Sakthi Nagaraj & Jeyapaul, 2021) further demonstrated that psychosocial and physical ergonomic factors exert stronger influence on lean performance than cognitive aspects, providing a more refined prioritization of human dimensions. Supporting this, (Dominguez-Alfaro et al., 2021) confirmed that ergonomic considerations can be integrated into value stream mapping without compromising productivity. Studies such as (Salma et al., 2021) and (Abu et al., 2022) identified recurring barriers—particularly weak

management commitment, insufficient training, and resistance to change—indicating that these human-related challenges have become globally consistent. Meanwhile, (Cardenas-Cristancho et al., 2022) identified human-related indicators as dominant predictors of lean performance, reinforcing their structural importance. Overall, this phase stabilizes the view that culture, commitment, knowledge, and ergonomics are routine components of lean analysis.

The system integration phase (2023–2024) reflects a stronger convergence between human factors and broader socio-technical systems, particularly in the context of Industry 4.0 and sustainability. (Ge, 2023) highlighted that intelligent manufacturing systems continue to face challenges related to human resource governance, indicating that technological advancement alone is insufficient. (Rathore et al., 2023) demonstrated that ergonomic and lean indicators can be integrated to identify intervention points, while (Szász et al., 2023) provided large-scale evidence that human resource practices increasingly contribute to performance improvement. Notably, (Ferrer et al., 2023) reported a negative relationship between certain human capital management practices and lean adoption, suggesting that institutional configurations of HR systems may influence outcomes. In 2024, (Saabye et al., 2024) emphasized the micro-foundations of lean leadership, linking it to learning and people development. Similarly, (Santoso & Kasih, 2024) showed that human resource practices mediate the relationship between lean and sustainable performance. These findings indicate that human factors are now deeply embedded within integrated frameworks that connect lean, sustainability, leadership, and digital transformation.

The human-centered maturity phase (2025–2026) represents the most advanced stage, where human factors are explicitly incorporated into maturity models, adaptive systems, and Industry 5.0 thinking. (Ganesan et al., 2025) demonstrated that lean transformation maturity depends on both technical capability and employee empowerment, although resistance to change and leadership gaps remain persistent challenges. (Pereira et al., 2025) identified human-cultural, organizational, and technical factors as interdependent drivers of performance, with employee involvement consistently emerging as central. (Heydarzade et al., 2025) introduced multi-layer value stream mapping incorporating human-centric metrics such as stress and fatigue, marking a shift toward holistic system optimization. In 2026, (Hines et al., 2026) proposed a human-centered integration model for lean and Industry 4.0, emphasizing the role of knowledge and skills, while (Alves et al., 2026) highlighted the need for age-sensitive ergonomic interventions, reflecting increasing attention to workforce diversity. These developments indicate that the field has evolved toward adaptive, inclusive, and human-centered system design.

Across the entire 2021–2026 period, several consistent patterns emerge. First, management commitment remains a dominant success factor across all lean-related implementations. Second, ergonomics has become fully embedded within lean frameworks, extending from assessment tools to integrated system design. Third, digital transformation is increasingly interpreted as a socio-technical process requiring training, empowerment, and collaboration. Fourth, organizational culture and employee involvement continue to mediate sustainable outcomes, particularly in SMEs. Finally, methodological approaches have become highly sophisticated, reflecting a mature research field where human factors are operationalized rather than merely conceptualized.

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In summary, Phase 4 represents the consolidation of human factors as a core organizing principle in lean manufacturing. The progression from stabilization (2021–2022), to integration (2023–2024), and finally to maturity (2025–2026) demonstrates that human factors are now fundamental to achieving sustainable, adaptive, and technologically advanced manufacturing systems.

Conclusion

This chronological review was conducted to systematically examine the evolution of research on human factors in lean manufacturing over the period from 2000 to 2026, based on a structured dataset retrieved from the Scopus database. The review focused on peer-reviewed journal articles filtered through rigorous inclusion criteria, resulting in a refined sample of 113 studies. The primary objective was to analyze how scholarly attention, research themes, and methodological approaches have developed over time, with particular emphasis on understanding the shifting role of human factors within lean systems.

The synthesis of chronological trends reveals a clear and progressive transformation of the research domain. Early studies were limited in number and primarily exploratory, reflecting a technical orientation of lean manufacturing with minimal emphasis on human dimensions. As the field progressed into the development and recognition phase, there was a noticeable increase in publication activity, accompanied by growing awareness of the importance of organizational culture, workforce engagement, and ergonomic considerations. The expansion phase marked a significant surge in empirical and model-driven research, integrating human factors with performance outcomes, digital technologies, and Lean Six Sigma practices. In the most recent stage, the field demonstrates consolidation, with research increasingly focusing on socio-technical integration, human-centered design, and alignment with advanced industrial paradigms such as Industry 4.0 and Industry 5.0.

Several dominant patterns and developments can be identified across the timeline. There is a clear shift from viewing human factors as supportive elements toward recognizing them as central drivers of lean success. Methodological advancements are evident, moving from conceptual discussions to quantitative modeling, simulation approaches, and integrated frameworks. Additionally, the incorporation of advanced technologies, including artificial intelligence and human–machine collaboration, reflects the evolving complexity of modern manufacturing systems. These developments indicate a maturing research field that increasingly adopts interdisciplinary perspectives and emphasizes the balance between technical efficiency and human well-being.

The chronological organization of the literature contributes significantly to the understanding of this field by providing a structured lens through which research evolution can be interpreted. Grouping studies by temporal phases enables clearer identification of shifts in focus, methodological refinement, and emerging themes that may remain obscured in traditional thematic reviews. This approach enhances analytical clarity, reveals hidden developmental patterns, and offers a coherent narrative of how human factors have gained prominence within lean manufacturing discourse over time.

From a practical and research perspective, the observed trends highlight the necessity of integrating human-centric strategies into lean implementation. Organizations are encouraged to prioritize employee involvement, leadership commitment, ergonomic design, and continuous learning to achieve sustainable performance improvements. For researchers, the evolution of this field underscores the importance of developing holistic frameworks that combine technical, organizational, and human dimensions, as well as exploring the implications of digital transformation and human–AI collaboration in lean environments.

Despite its contributions, this review is subject to certain limitations. The reliance on a single database may have excluded relevant studies from other sources, while the use of specific keywords could limit the breadth of retrieved literature. Additionally, the time frame and filtering criteria may restrict the inclusion of emerging or interdisciplinary works. Future research is therefore encouraged to adopt multi-database approaches, expand keyword strategies, and explore cross-disciplinary perspectives. Greater emphasis should also be placed on real-world industrial applications, longitudinal case studies, and the integration of human factors within rapidly evolving technological contexts.

In conclusion, the findings demonstrate that chronological reviews play a critical role in capturing the dynamic progression of scientific research. By structuring knowledge according to temporal development, such analyses provide valuable insights into the transformation of research domains, support evidence-based decision-making, and guide future innovations. In the context of human factors in lean manufacturing, time-based analysis offers a comprehensive understanding of how the field has evolved and continues to adapt, reinforcing its importance in shaping sustainable and human-centered industrial systems.

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