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A Systematic Bibliometric Review and Visualization of the Intersection between Lean Management and Industrial Revolutions

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Abstract

The convergence of Lean philosophy with the paradigms of Industry 4.0 (IR4.0) and Industry 5.0 (IR5.0) is emerging as a persuasive area of research and industrial practice. A bibliometric and network analyses indicate a growing scientific and industrial interest, particularly in Europe and emerging economies, underscoring the interdisciplinary nature of this field. While initial studies concentrated on technological foundations and operational performance, this study has shifted focus toward digital transformation, sustainability, and human-centric approaches. Lean principles are being enhanced by IR technologies like IoT, AI, and advanced analytics, facilitating real-time monitoring and dynamic process optimization. The transition to IR5.0 highlights the importance of human-centricity and societal resilience, positioning the fusion of Lean and advanced technologies as a pathway to operational excellence, along with broader environmental and societal benefits. However, notable research gaps persist, particularly regarding practical integration mechanisms across diverse contexts and non-manufacturing sectors. Addressing these challenges necessitates organizational transformation, workforce upskilling, and interdisciplinary collaboration. The integration of Lean principles with IR4.0 and IR5.0 presents industries with a strategic opportunity to improve efficiency, sustainability, and innovation, provided that human and social factors are prioritized alongside technological progress.

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1. Introduction

The integration of Lean philosophy with the Industrial Revolution (Industry 4.0 and Industry 5.0) is a growing area of interest, focusing on enhancing efficiency, sustainability, and human-centric approaches in industrial contexts. This synthesis explores the challenges and the future directions of combining these paradigms. The integration of Lean philosophy and management with Industry 4.0 (IR4.0), often referred to as Lean 4.0, is a growing area of interest in both academic and industrial circles [1]. This integration aims to combine the waste reduction and efficiency principles of Lean with the advanced technological capabilities of IR4.0 to enhance productivity, flexibility, and sustainability in manufacturing and other industries [2].

While previous studies provide valuable insights into the relationship between lean philosophy and these industrial and educational paradigms [3], there is limited direct information on the specific applications of lean philosophy in the context of IR4.0 and IR5.0. However, some academic scholars argue that the integration of new IR technologies may fundamentally alter or even contradict the foundational principles of Lean philosophy [4].

Lean philosophy seeks to maximize value creation while minimizing waste by streamlining processes, reducing unnecessary resource use, and fostering continuous improvement to sustain effectiveness, flexibility, and profitability [5–7]. IR4.0 technologies, such as Internet of Things (IoT), cloud computing, and Artificial Intelligence (AI), amplify Lean manufacturing's efficiency by providing real-time data and flow automation, which streamline processes and reduce waste [8]. Aligning the simplicity of Lean management with the complexity of Industry 4.0 requires a significant cultural transformation within organizations [9]. This transformation is especially important in areas such as change management, employee empowerment, and digital readiness. Empirical studies show that successful integration necessitates a shift from traditional hierarchical structures to more decentralized, flexible, and transparent workflows [10]. This approach should be supported by values such as continuous improvement and openness to technological innovation. However, resistance to this shift can often occur due to factors like a lack of technological familiarity, insufficient management support, or anxiety about job displacement. This phenomenon highlights the critical roles of leadership, training, and workforce engagement in facilitating the transition.

IR4.0 technologies can support Lean Human-Centric (HC) actions, enhancing traditional sectors like fashion and construction by integrating human-robot collaboration and other assistive technologies [11]. IR5.0 emphasizes human-centricity, resilience, and sustainability [12]. The transition from IR4.0 to IR5.0 represents a paradigm shift towards more human-centric and sustainable manufacturing practices. This theme addresses the challenges and opportunities associated with the integration of advanced technologies with human-centered approaches to create more resilient and adaptive manufacturing systems.

The research gap identified in the manuscript focuses on the insufficient empirical and theoretical understanding of the mechanisms and best practices for integrating Lean management principles with Industry 4.0 and Industry 5.0 technologies, particularly beyond the manufacturing sector and across various socio-economic contexts. While the literature increasingly addresses topics, e.g., digital transformation, sustainability, and human-centric approaches, it provides limited insights into how organizations can steadily achieve effective integration of Lean methodologies with advanced industrial technologies.

This rationale supports the selection of a bibliometric review and visualization analysis as an effective method for enhancing our understanding of the intersection between Lean management and the Industrial Revolutions. A bibliometric analysis makes a distinct contribution to the existing literature by systematically quantifying and visualizing the development, structure, and dynamics of research pertaining to Lean management and Industrial Revolutions (IR4.0 and IR5.0). In contrast to traditional qualitative content analysis, bibliometric methods allow for the examination of a substantial body of literature, enabling the identification of research trends, influential authors and institutions, collaboration networks, and emerging thematic areas through citation and keyword co-occurrence analysis.

This bibliometric analysis aims to help researchers and practitioners understand the development of industrial technologies and consider perspectives related to lean management. We will examine a variety of research areas to nuance the findings and provide valuable theories and methods used in industrial development, such as combining Lean principles with new technologies, focusing on people and machines working together, using real-time data to improve processes, and creating systems that are adaptive, efficient, and sustainable. By drawing a holistic perspective,

this analysis also calls for further evidence and using the latest bibliometric methodologies to better understand the broader socio-economic impacts of industrial development.

2. Theoretical Foundations and State of the Art

The intersection of Lean philosophy with the paradigms of Industry 4.0 and Industry 5.0 lies at the convergence of several theoretical disciplines. Traditional lean management theory emphasizes systematic waste elimination and continuous improvement to maximize value creation[6]. However, integrating Industry 4.0's digital technologies demands an exploration of socio-technical systems theory, which highlights the importance of aligning technological assets with human and organizational factors to achieve resilient operations [13].

Theories of organizational change and innovation diffusion provide a theoretical framework for understanding how manufacturing firms can adopt Industry 4.0 technologies while upholding lean principles, illuminating challenges such as employee readiness, leadership commitment, and cultural transformation [14]. The academic focus on sustainability and human-centric approaches in Industry 5.0 further expands the theoretical landscape by emphasizing ecological impacts and worker well-being alongside productivity [15].

Our bibliometric analysis supports a gradual thematic progression from technological enablers, such as IoT, AI, and cyber-physical systems, to considerations of sustainability, circular economy, and human factors [16]. Despite these advancements, the literature reveals conceptual gaps in integrating various theoretical perspectives to inform practical applications across diverse industrial contexts and economic environments. Addressing these gaps requires an interdisciplinary theoretical synthesis that encompasses operations management, information systems, and social sciences to fully understand the complexities of lean transformations in the age of advanced industry.

3. Data and Methods

We employed a Systematic Literature Network Analysis (SLNA) to carefully select and assess relevant literature regarding the integration of Lean management with the Industrial Revolution stages. The data collection process was thorough, encompassing literature available up to June 30, 2025. Our search commenced in 2015, a key year when the principles of Lean management began to align with the concepts of the Industrial Revolution. The methodology included a bibliometric review, which enabled the systematic identification of appropriate search terms tailored to the research questions. Throughout this process, the irrelevant articles and duplicates were excluded, thereby refining the dataset to enhance the quality and relevance of our findings (Figure 1).

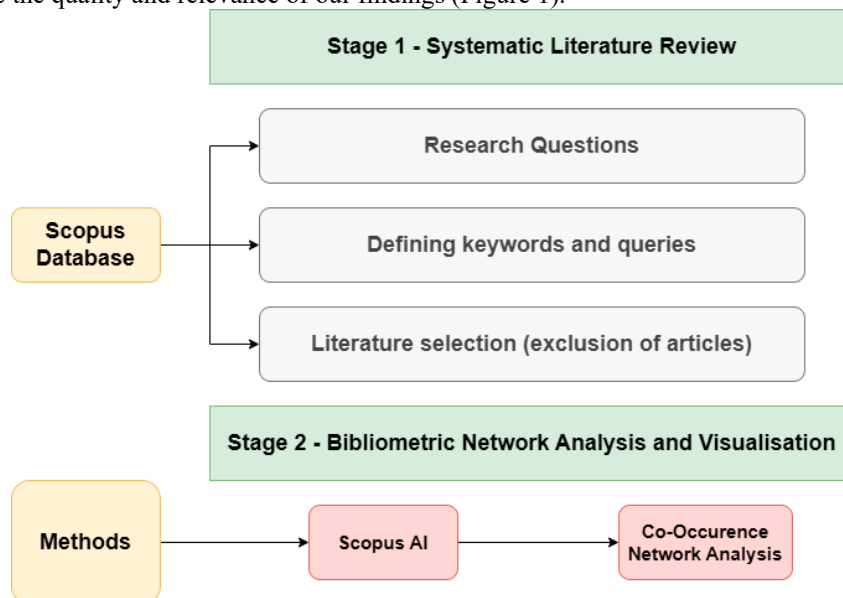


Fig. 1. Framework of the Bibliometric Review and Visualization.

The review was conducted with attention to detail using the document search of the Scopus database [17], a leading resource for international literature research. Scopus is particularly beneficial for distinguishing between publications authored by individuals with common names, thanks to its advanced filtering and indexing techniques, which enhance the accuracy of citation analysis [17]. One of the standout features of Scopus is the offering of comprehensive author and institutional profiles, which provide valuable insights into individual research contributions and their institutional affiliations. Additionally, it grants access to a wealth of author and source information, including citation and metrics values and AI tools, which are essential for assessing academic impact and productivity [18]. Furthermore, the vast size and diversity of the publication collection make it an exceptional choice for bibliographic analysis, allowing researchers to identify trends and key contributors across various fields and conduct thorough literature reviews. This combination of attributes reinforces Scopus as a leading resource in the academic research landscape [19].

The initial phase of the analysis concentrated on the distribution of documents, emphasizing transparency and clearly articulating the explanatory features of the research. Our research question (RQ) specifically investigates: What are the primary approaches that should be considered for effectively integrating Lean philosophy with the frameworks of the Industrial Revolution? This inquiry seeks to uncover and explore the foundational strategies and methodologies that facilitate the synthesis of these two significant paradigms, ultimately contributing to advancements in operational efficiency and innovation.

Advanced bibliographic network analysis and visualization techniques are employed to enhance the understanding of current and emerging research topics. Specifically, the Co-Occurrence Network (CON) analysis will be utilized. The CON method will allow us to map the relationships between keywords within the literature, thereby revealing trends and connections among various research areas. In parallel, it offers a metric for evaluating the impact of specific research contributions based on their association patterns across different scholarly publications.

These analytical methods not only keep information about the latest developments in the research field but also contribute to a comprehensive and nuanced understanding of qualitative aspects that complement bibliometric analysis. By systematically analyzing the titles, abstracts, and author-provided keywords of relevant studies, we can conduct a thorough content analysis using search techniques. This approach significantly reduces potential bias, resulting in more reliable outcomes and improved accuracy in addressing our research inquiries. Ultimately, the emphasis on these detailed methodologies will facilitate a robust exploration of the scholarly landscape and enable informed decision-making and strategic research directions.

The open-access software package VOSviewer (1.6.20) provides a robust platform for bibliometric mapping and visualization. The tool is particularly effective for analyzing datasets obtained from Scopus, allowing for systematic and in-depth examination of scholarly literature. At the core of its capabilities is the Visualization of Similarities (VOS) algorithm, which skillfully visualizes both direct and indirect relationships among various entities within a dataset. This algorithm generates a network map in which the proximity of nodes indicates the frequency with which specific entities co-appear in the research literature. The nodes that are closer to one another reflect a higher degree of co-occurrence.

Additionally, each element displayed on the network and layout maps is positioned in prominent central locations, suggesting that it represents broader, more diverse groups of related elements [20]. This arrangement facilitates a clearer understanding of significant clusters of research themes, which are visually differentiated through color coding. Such visualizations aid in identifying prolific authors and the most cited works within academic fields. By utilizing VOSviewer, researchers can uncover valuable insights into influential research domains and trace the evolution of these areas over time. Moreover, the software not only reveals the structure of academic literature but also promotes a comprehensive analysis of trends, empowering scholars to navigate the complexities of research outputs effectively.

4. Visualization Results of the Literature

We conducted a review of the literature within the Scopus database, investigating relevant terms, synonyms, and abbreviations associated with the Lean and Industrial Revolution. Utilizing the query command TITLE-ABS-KEY, we examined the titles, abstracts, and keywords of publications, focusing on the identified terms, including lean topics (and their synonyms) and phrases related to the Industrial Revolution (IR4.0 and IR5.0) as illustrated in EQ1.

TITLE-ABS-KEY(("lean philosophy" OR "lean management" OR "lean thinking" OR "Lean 4.0") AND ("Industry 4.0" OR "Industry 5.0")) (1)

The selected terms represent the essential and widely acknowledged terminology associated with Lean principles and their direct integration into the paradigms of Industry 4.0 and Industry 5.0, as established in the literature. The focus was deliberately narrowed to specifically encompass publications that discuss Lean philosophy and management frameworks in relation to the current and emerging industrial revolutions, ensuring both relevance and specificity. Terms such as "smart manufacturing" and "digital lean" were initially excluded to prevent the query from expanding into adjacent yet distinct areas that could dilute the focus on Lean principles.

A total of 333 research articles were reviewed by the end of the submission period. For further analysis, we included only articles, conference papers, book chapters, books, reviews, conference publications, short surveys, and notes, all of which were published in English.

4.1. Distribution of research documents

Figure 2. illustrates the annual distribution of documents published in the Scopus database concerning the topics of "lean" and "Industry 4.0/5.0" from 2015 to 2025. A steady increase in publications began in 2017, culminating in approximately 28 documents by 2019. In 2020, there was a notable surge, with the number of publications rising to nearly 45. Following a slight decline in 2021, growth resumed from 2022 onwards, with around 60 documents published in 2023 and peaking at approximately 63 in 2024.

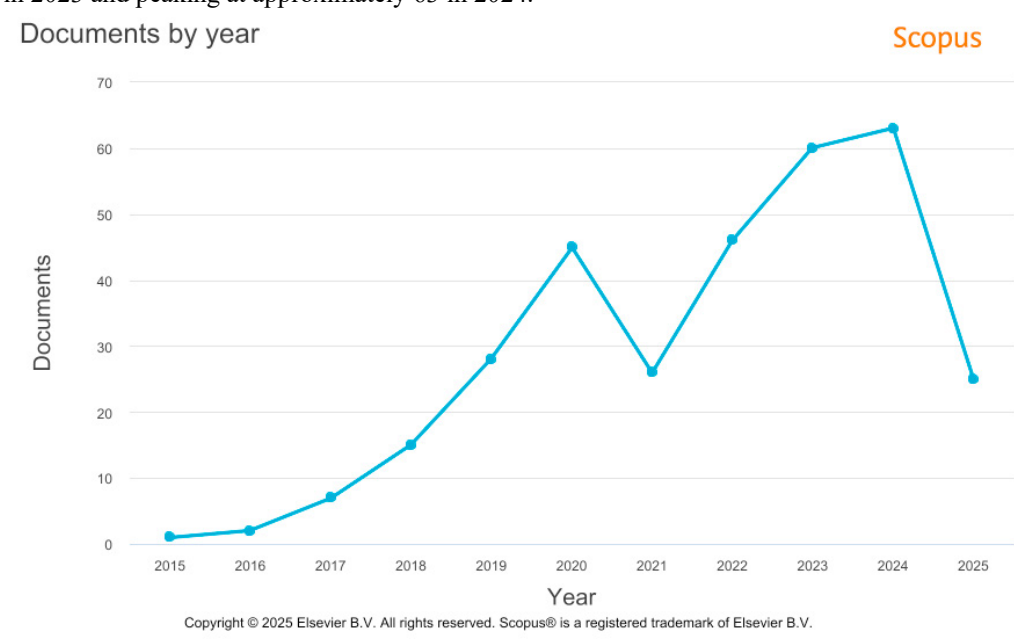


Fig. 2. Documents by year.

The results of data indicate that scientific interest in the intersection of "lean" and "Industry 4.0/5.0" began to rise significantly in 2017, highlighting, for instance, the growing integration of digitalization, the industrial revolution, and lean management practices. The spike in 2020 may be attributed to the COVID-19 impact, which emphasized the need for industrial digitalization and efficiency. After a brief decline in 2021, research interest rebounded, reaching its apex in 2023-2024. Throughout the examined period, the volume of publications related to "lean" and "Industry 4.0/5.0" has seen substantial growth in the last five years, underscoring the increasing scientific and industrial relevance of the subject. Research activity has shown consistent growth throughout the study period, with a steady increase in the number of publications from 2017 onward, culminating in a peak of approximately 63 documents in 2024. While there were some minor fluctuations in 2021, the overall trend demonstrates a strong upward trajectory in scholarly interest [exact numbers or figure reference].

Figure 3 presents the distribution of research documents related to "lean" and "Industry 4.0/5.0" by country, based on Scopus data by country and territory. Italy leads with the highest number of publications (nearly 48), indicating

strong research activity and interest in integrating lean principles with Industry 4.0 and 5.0 concepts. Portugal and Germany follow, each contributing more than 35 documents, reflecting significant engagement from Western and Southern Europe. Brazil and India are notable contributors, each with over 25 publications, highlighting the growing importance of these topics in emerging economies and their manufacturing sectors. Morocco stands out among African nations, with around 27 documents showing increasing research output from North Africa. Canada, France, Spain, and the United Kingdom each contribute around 20 documents, indicating a broad European and North American research interest. The dominance of Italy, Portugal, and Germany suggests that European countries are at the forefront of research on lean and Industry 4.0/5.0 integration, likely due to their advanced manufacturing sectors and strong academic-industry collaboration. The significant presence of Brazil and India demonstrates that these topics are not limited to developed economies; they are also gaining traction in rapidly industrializing regions. The diversity of countries/territories in the top 15 (spanning Europe, Asia, South America, and Africa) underscores the global relevance and widespread academic interest in the synergy between lean methodologies and advanced industrial revolutions.

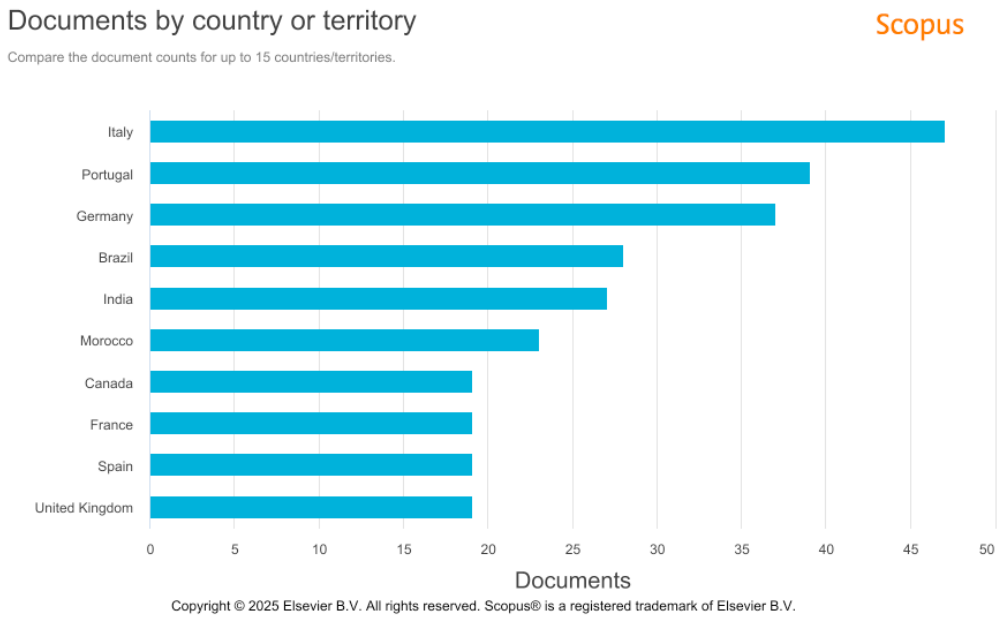


Fig. 3. Documents by country.

The pie chart illustrates the distribution of research documents pertaining to "lean" and "Industry 4.0/5.0" by subject area, as derived from Scopus data (Figure 4). Engineering emerges as the predominant field, accounting for 28.2% of the total documents. This statistic underscores the robust interrelation between lean principles, industrial processes, and the technological advancements characteristic of IR4.0 and IR5.0. Following engineering, Business, Management, and Accounting represent the ^{second} largest category at 16.4%. This result highlights the significance of organizational strategy, process optimization, and management practices in the implementation of lean methodologies and digital transformation initiatives.

Computer Science, with a contribution of 15.7%, closely follows, reflecting the integral role of digital technologies, automation, and data analytics in both lean manufacturing and Industry 4.0/5.0 endeavors. Decision Sciences accounts for 12.0%, emphasizing the importance of data-driven decision-making, operations research, and optimization within these domains. Other areas of study, including Environmental Science (3.8%), Social Sciences (3.5%), Chemical Engineering (3.4%), Energy (3.1%), Mathematics (3.1%), and Economics, Econometrics, and Finance (2.8%), each contribute a smaller yet notable share, illustrating the interdisciplinary interest and broad applicability of lean and Industry 4.0/5.0 concepts. Collectively, other subject areas constitute 7.9%, indicating additional, albeit less dominant, fields engaged in this research.

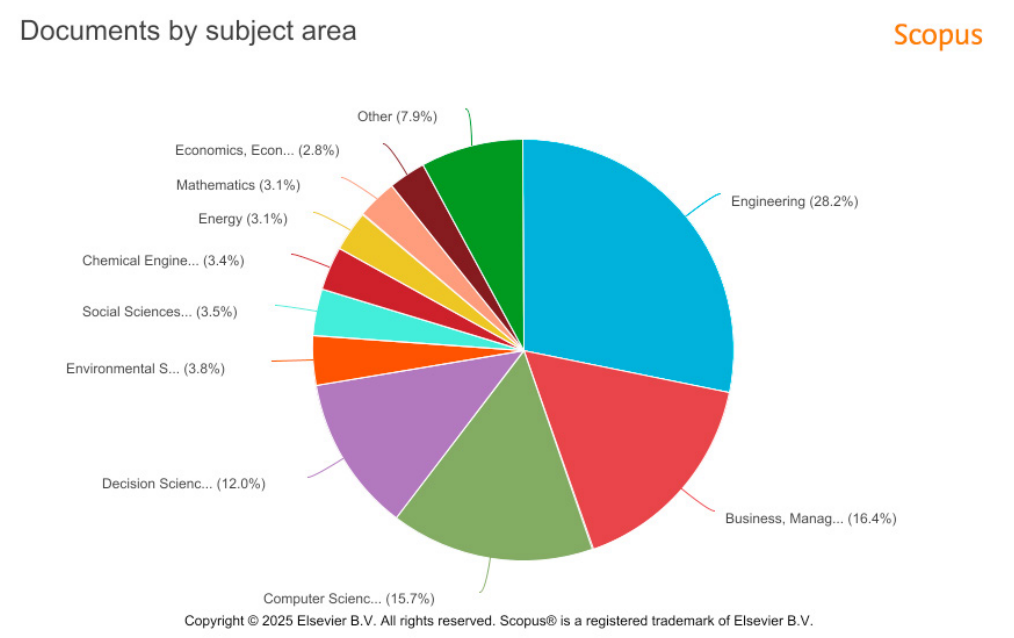


Fig. 4. Documents by subject area.

The predominance of engineering and related technical disciplines indicates that research on Lean and Industry 4.0/5.0 is primarily driven by initiatives aimed at innovating and optimizing industrial systems and processes [21]. The extensive presentation of business and management literature signifies that, beyond technological advancements, aspects such as organizational change, leadership, and strategic planning are essential for successful implementation [22]. Additionally, the significant involvement of computer science and decision sciences suggests that digitalization, automation, and advanced analytics are central to the progressive evolution of lean practices within the modern industrial context. Furthermore, the engagement of environmental and social sciences reflects an increasing emphasis on sustainability and the societal implications of technological, organizational, and cultural transformations associated with lean and Industry 4.0/5.0.

4.2. Co-Occurrence Network (CON) of Keywords Analysis

We utilize Co-occurrence Network analysis in conjunction with cluster analysis techniques to perform a thorough analysis of author keywords. In this network representation, each item is visually depicted by its assigned label and is presented in a square shape, which helps differentiate between various categories or types of keywords. The size of each shape corresponds to its weight, effectively indicating the keyword's significance within the dataset [23]. The nodes in the network represent the selected keywords, with their varying sizes serving as a visual indicator of their relative importance and prevalence in the literature. Larger nodes signify keywords that occur more frequently or are more influential, while smaller nodes denote those of lesser significance [24]. Labels with low frequency of occurrence (e.g., keywords appearing below a certain threshold count) were excluded to focus on more impactful terms. This methodology facilitates a meaningful exploration of the interrelationships among keywords and aids in identifying prevailing trends within the scholarly discourse.

The VOSviewer Network (overlay) map (Figure 5) illustrates the relationships and temporal evolution of key terms in the literature concerning Lean and IR4.0/5.0 from 2021 to 2023. The most prominent and central nodes are "industry 4.0," "lean 4.0," "lean manufacturing," "lean thinking," and "lean management." Their central positioning and dense interconnections signify that these topics are fundamental to the research field, acting as hubs that connect to a wide array of related concepts.

The color gradient, transitioning from blue to yellow, which is the most topical, indicates the average publication year of documents in which each term appears.

Human Touch, involves automating processes to detect defects and stopping to prevent defective products. Automation technologies, such as Autonomous Guided Vehicles (AGVs) and machine learning (ML), improve the ability to identify and address issues promptly, ensuring higher quality and efficiency [32]. Lean systems are designed to be flexible and responsive to changes in demand. The use of Creative Problem Solving and flexible manufacturing systems allows for rapid adjustments to production processes, improving responsiveness to market changes [33]. The lean philosophy values the involvement and continuous development of employees. Lean Digital Education (LDE) in new technologies and fostering a culture of continuous improvement is essential for successfully integrating IR4.0/5.0 with lean principles [34]. Ultimately, lean aims to create more value with fewer resources, contributing to sustainability. Technologies, such as IoT and AI, can optimize resource usage and reduce environmental impacts, aligning with Sustainable Development Goals SDGs [35]. For instance, IoT-enabled smart sensors can monitor energy consumption in real time, enabling dynamic adjustments that reduce waste and emissions, contributing to SDG 12 on sustainable consumption and production [36].

5. Conclusion and Implications

The convergence of Lean philosophy with the paradigms of the Industrial Revolution (IR) is emerging as a dynamic and evolving area of research and practice. Bibliometric and network analyses reveal increasing interest from the scientific community and industry. This trend highlights not only the academic significance but also the practical importance of merging lean methodologies with advanced industrial technologies.

Research in this field is primarily led by European countries, particularly Italy, Portugal, and Germany, while also featuring substantial contributions from emerging economies such as Brazil and India. The discipline is inherently interdisciplinary, encompassing areas such as engineering, business and management, computer science, and decision sciences. Initial studies tended to concentrate on foundational technological aspects and operational performance. In contrast, more recent research has shifted towards topics such as digital transformation, integration, and sustainability. The rise of IR5.0, along with an emphasis on machine learning, circular economy, and human-centric approaches, signifies a move towards intelligent, resilient, and sustainable manufacturing systems.

Lean principles are being enhanced by IR technologies like IoT, AI, and advanced analytics. These technologies facilitate real-time monitoring, predictive maintenance, and dynamic process optimization, thus supporting lean objectives and fostering continuous improvement. The transition to IR5.0 emphasizes a renewed focus on human-centricity, resilience, and sustainability. The integration of advanced technologies with lean management is viewed as a pathway not only to achieve operational excellence but also to deliver broader societal and environmental benefits.

The findings of this bibliometric analysis carry implications for researchers, practitioners, and policymakers. Successfully merging Lean practices with IR4.0/5.0 necessitates not only technological adoption but also fundamental organizational and cultural transformations. Essential components include education, change management, and the cultivation of new technical skills and interpersonal competences to bridge the divide between the simplicity of Lean methodologies and the complexities of advanced technologies. The relationship between Lean principles and digital technologies creates new avenues for innovation across manufacturing and other sectors. Leveraging real-time data, automation, and augmented human-centric lean can enable organizations to achieve enhanced levels of efficiency, flexibility, and responsiveness [37]. This integration aligns with global sustainability objectives by fostering resource optimization and minimizing environmental footprints. The human-centric focus of IR5.0 underscores the importance of ensuring that technological advancements contribute positively to workforce well-being and societal resilience.

Despite a growing body of literature, there are still significant gaps in our understanding of the specific mechanisms and best practices for integrating Lean with IR4.0/5.0, particularly within non-manufacturing sectors and diverse socio-economic contexts. Further theoretical research, empirical findings, and case studies are essential to develop comprehensive frameworks and guidelines. Policymakers and educational institutions should facilitate and encourage interdisciplinary and national collaboration and invest in workforce upskilling to support the digital transformation of Lean systems. This investment will be vital for maintaining competitiveness of companies and fostering inclusive industrial development.

While the technological aspects of Industry 4.0 are well understood, there is an increasing acknowledgment of the necessity to address human and social factors, such as leadership, training, and organizational culture, to harness the benefits of Lean 4.0 [38]. Additionally, more empirical research is required to investigate the practical implications

of integrating Lean principles with Industry 4.0, particularly across various industrial contexts, such as agricultural environments and Small and Medium-sized Enterprises (SMEs) [39]. The concept of SME 5.0, referring to intelligent, sustainable, and human-centred SMEs, is emerging in the literature [40]. Intelligent, Sustainable and Human-Centred SMEs (SME 5.0) often encounter difficulties in justifying investments in IR technologies due to limited capital [41].

A methodical approach to digitalization and data management is recommended for SMEs, beginning with essential steps such as digitizing current workflows and incorporating basic IoT sensors for real-time monitoring. Alongside technology adoption, it is important to implement gradual upskilling programs tailored to various roles within the organization. Initiating pilot projects in selected areas allows for testing solutions before broader implementation. Additionally, forming partnerships with technology providers and academic institutions can enhance customized support and drive innovation. This phased strategy not only enables manageable investments and mitigates risks but also promotes continuous improvement in line with lean principles.

The Lean philosophy aligns with their principles, fostering the development of Lean 5.0 [42]. Both paradigms play a vital role in addressing sustainability challenges by promoting eco-friendly practices and optimizing resource utilization [43]. The integration of lean principles with IR4.0 and IR5.0 technologies presents a synergistic approach to achieving enhanced efficiency, waste reduction, and improved responsiveness in manufacturing. These fusion leverages advanced technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), machine learning, and digital twins, to enhance traditional lean practices such as value stream mapping, continuous improvement, and just-in-time (JIT) production. For instance, IoT-enabled sensors provide real-time data for value stream mapping, facilitating the dynamic identification and elimination of bottlenecks. Meanwhile, AI-driven predictive analytics enhance just-in-time scheduling by accurately forecasting demand, thereby reducing inventory levels, and minimizing waste.

This study offers valuable insights into the intersection of Lean management and Industrial Revolutions through a bibliometric approach. However, several limitations should be considered. Most notably, the analysis relies solely on the Scopus database, which, while comprehensive, may exclude pertinent publications indexed in other databases, e.g., Web of Science (WoS), IEEE Xplore, or Google Scholar. This choice of database may introduce a common bias, potentially privileging certain disciplines, regions, or types of publications. Furthermore, bibliometric methods are inherently dependent on the quality and accuracy of metadata, which can influence network analyses and thematic interpretations. Future research could enhance understanding in this evolving field by integrating multiple databases and complementary qualitative analyses (e.g., PRISMA) for a more comprehensive and nuanced perspective.

In summary, the convergence of Lean philosophy with IR4.0 and IR5.0 presents a transformative opportunity for industries, promising improved efficiency, sustainability, and human-centric innovations. Ongoing international research, cross-sector collaboration, and skill development are essential to realize the benefits of integrating Lean with Industry 4.0 and 5.0

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