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Review article

Lean ergonomics: A three-dimensional analysis of progress, practical challenges, and prospective research

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ABSTRACT

Lean systems and ergonomics are two organizational approaches that were initially practiced independently. Over time, however, it has become evident that while lean methodology emphasizes efficiency and waste reduction, it often overlooks the human factor, which can compromise worker health and safety. On the other hand, applying ergonomics without incorporating lean principles may lead to inefficiencies and increased costs. This trade-off has sparked growing interest in integrating ergonomic considerations into lean practices within manufacturing. Despite this interest, comprehensive studies on lean ergonomics remain scarce. This research aims to explore the development of lean ergonomics implementation over the past five years. Using a Systematic Literature Review (SLR) methodology, the study analyzed articles from two Scopus-indexed databases, identifying 196 articles containing the keywords *Lean*, *Ergonomics*, and *Manufacturing Industries*. Following the PRISMA framework and applying inclusion criteria, only 18 papers were found to thoroughly address the integrated implementation of lean ergonomics in manufacturing industries. The majority of these studies originated from Portugal (33.33%) and India (16.67%). Case studies emerged as the dominant research methodology (55.56%), leading to the development of lean ergonomic tools such as Ergo-VSM, ErgoSMED, and WIDEA. Other methodologies included literature reviews (22.22%), qualitative research (16.67%), and grounded theory (5.56%). The findings suggest that implementing lean ergonomics has positive impacts, including reduced setup times, decreased ergonomic risks, and improved workplace conditions. While ergonomic interventions may involve additional costs, these are viewed as long-term investments. In conclusion, the existing literature indicates that the implementation of lean ergonomics is still limited and lacks comprehensiveness. Future research could focus on practical applications in industry and evaluate their effectiveness to strike a balance between operational efficiency and worker well-being.

1. Introduction

Lean manufacturing represents a comprehensive system oriented towards continuously increasing value (continuous improvement) by minimizing activities that do not provide added value (waste). Initially developed in the manufacturing sector, lean principles have now expanded to various fields, including healthcare, government, education, and more. The tools and techniques associated with lean help organizations implement core principles aimed at enhancing productivity and efficiency. Some professionals view lean as a gradual progression from mature quality control and just-in-time inventory philosophies, while others consider it a radical shift in thinking patterns, behavior, and organizational culture [1].

Lean manufacturing provides a series of techniques and tools that must be applied thoughtfully and situationally to realize their benefits. There is no universal formula for balancing and optimally applying these instruments; their use must be determined individually based on the specific circumstances, unique vision, and attributes of each organization adopting lean principles. Effective and customized integration of lean practices requires an understanding of the underlying lean philosophy, combined with adaptation to fit the specific organizational context. Blindly utilizing lean tools without a fundamental understanding or alignment with organizational

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characteristics is likely to fail in producing meaningful improvements. Although lean offers many benefits, success depends on flexible and adaptive implementation rather than rigid, blanket application [2].

Lean methodology involves complex tools and has been proven effective in improving system performance. However, in practice, lean implementation can create ergonomic problems for workers, who are the most vital assets in an organization. Lean implementation often places the burden of difficulties on workers, highlighting the need for potential modifications to alleviate these issues [3]. Most users tend to focus solely on lean tools and techniques (hard lean practices) while neglecting human factors and ergonomics (soft lean practices) during the implementation of lean in an organization. Consequently, concentrating exclusively on hard lean practices can negatively impact the Quality of Work Life (QWL) for workers [4].

A review of the existing literature on lean manufacturing reveals many unexplored areas of research, including a significant knowledge gap regarding the implications of human factors in the application of lean principles [5]. A survey of industry executives indicated that their general perspective is that ergonomics serves primarily as a tool to protect health and prevent disease, rather than as a technique to improve cost efficiency and reduce waste. However, academic literature clearly demonstrates the synergistic potential of combining lean manufacturing with ergonomic principles to simultaneously enhance productivity and improve working conditions. Creating a workplace that aligns with both lean and ergonomic values will boost productivity for employees and the organization as a whole [3]. Additionally, it is noted that the existing literature on the relationship between lean manufacturing principles and workplace health and safety remains scarce and is characterized by weak research methodologies [6].

Based on the information above, we are interested in exploring the implementation of lean ergonomics through existing studies to understand its development, impacts, and the gaps in the current literature. By identifying these gaps in research, it is hoped that this work will provide valuable insights that will guide future research to enhance the integration of lean ergonomics in manufacturing practices.

2. Material and method

2.1. Research questions

This literature review begins by establishing the research idea through the utilization of various article search tools, specifically using the keywords "Lean Ergonomics" in the manufacturing industry. The tools employed to generate this idea include Connected Papers, Open Knowledge Maps, and the AI platform ChatGPT. The use of these resources serves to reinforce the viability of the research idea as a significant topic for literature investigation.

Using Connected Papers, the topic of Lean Ergonomics was explored, resulting in an interactive graphic display as shown in Fig. 1. In the search, 41 related articles were identified, with 21 of them published in the last five years (2019-2023). This indicates that the topic is still relatively underexplored, presenting an opportunity for more in-depth and extensive research. Meanwhile, using the same keyword search on Open Knowledge Map, a map was obtained as shown in Fig. 2, where 45 articles related to the keyword were obtained.

In the map, the integration of lean principles and ergonomic approaches is evident in the overlapping areas related to automation, human factors, and manufacturing systems. This connection underscores the importance of combining efficiency-driven lean methodologies with ergonomic considerations to enhance both productivity and worker safety. The intersection with occupational safety and risk management further highlights the focus on creating streamlined processes that do not compromise employee well-being. This comprehensive approach aims to achieve sustainable manufacturing practices that balance operational efficiency with the health and comfort of the workforce.

The search was also tested using ChatGPT, an Open AI Platform, by asking whether Lean Ergonomic studies in the manufacturing industry are studies that are rarely carried out? The answer from the machine is: “Lean ergonomic practices in the manufacturing industry are gaining attention as organizations increasingly recognize the importance of combining lean principles with ergonomic considerations to improve efficiency, worker well-being, and overall productivity. However, the prevalence and depth of research on lean ergonomics may vary, and the adoption of such practices could be affected by elements like the type of business sector, organizational culture, and regional differences”. Based on this answer, it opens up an opportunity to discuss how the impact of implementing lean ergonomics in the production sector, it yields beneficial outcomes for the company.

The study of Lean Ergonomics analysis in manufacturing has begun to be researched since 1999. The integration of lean manufacturing principles with ergonomic considerations, represents an emerging methodology with limited extant literature. Through systematic research across diverse industrial sectors, it is possible to augment the body of knowledge regarding the implementation of this integrated approach. This amalgamation of lean manufacturing and ergonomics aims to minimize inefficiencies in human activities, which are typically classified as waste. Consequently, this approach has the potential to enhance process efficiency while simultaneously mitigating ergonomic risks [7].

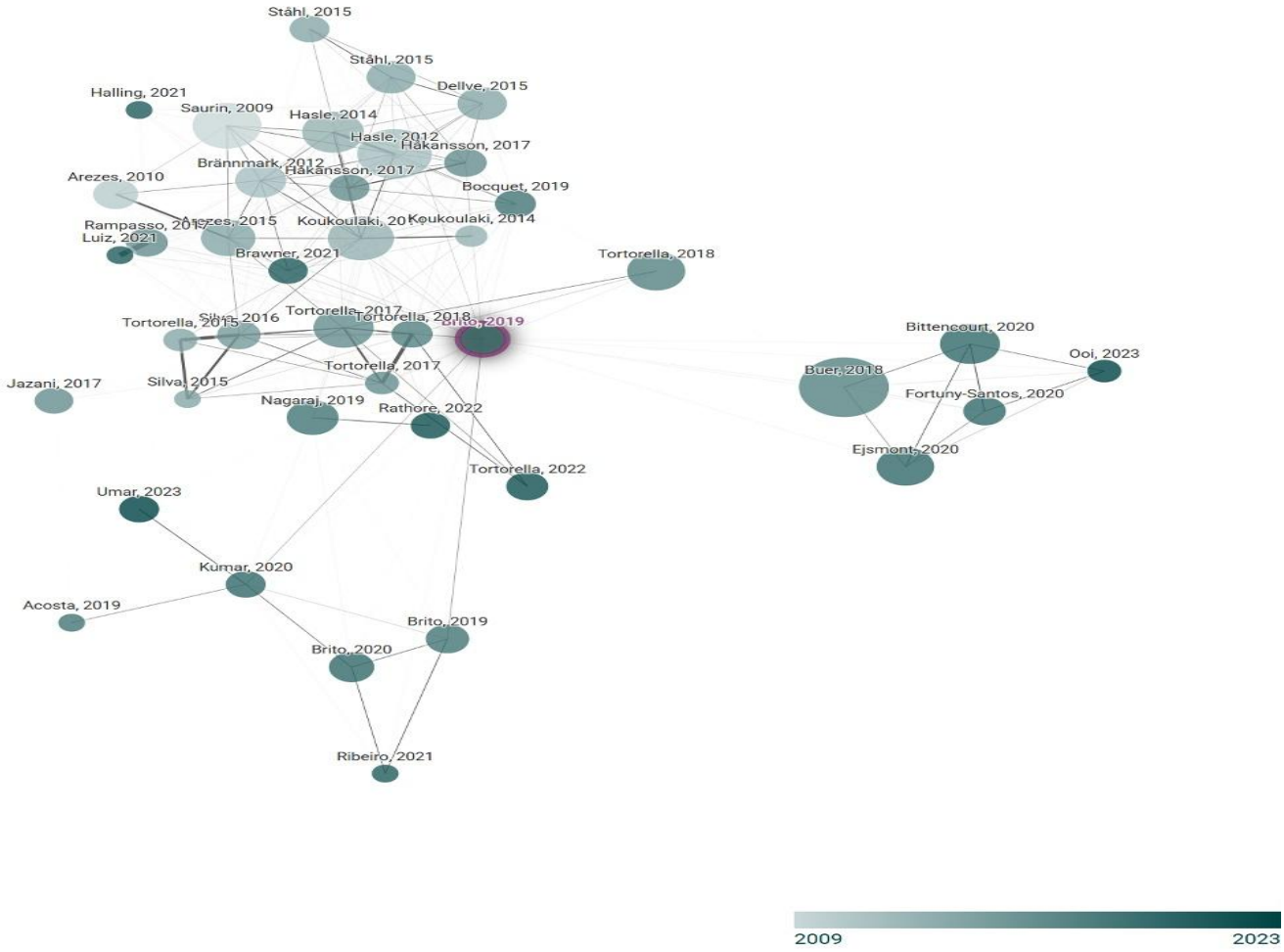

Figure 1. Search for the keyword "lean ergonomics in manufacturing industry" on connectedpapers.com

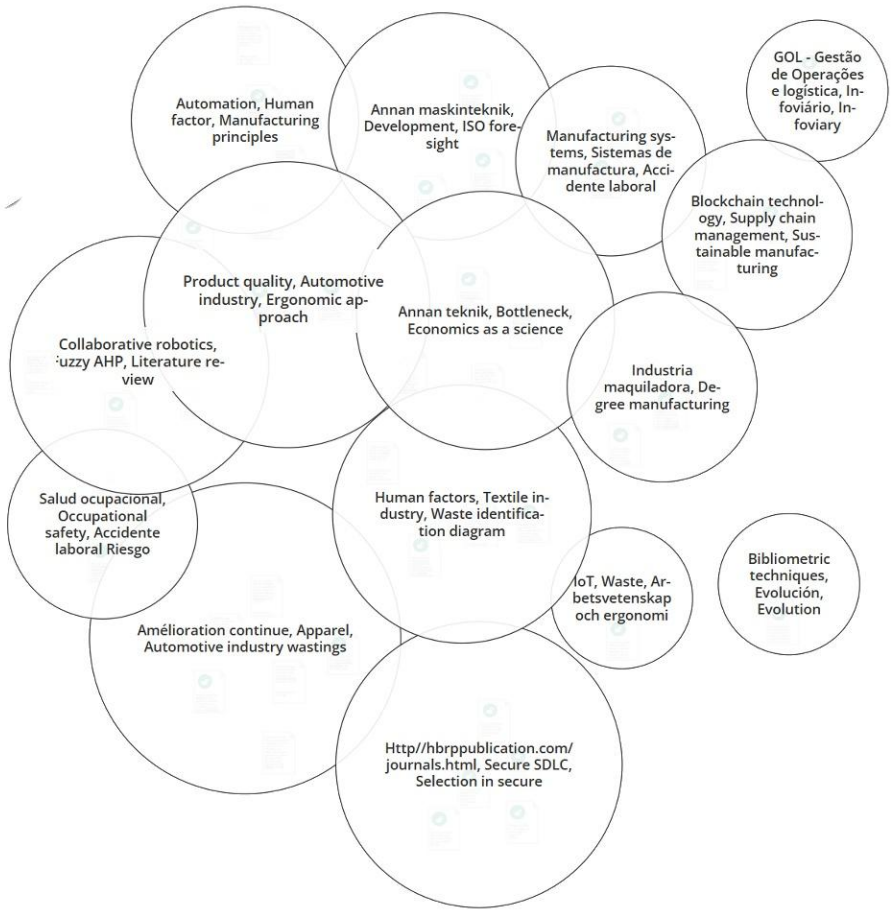

Figure 2. Open Knowledge Maps lean ergonomics in manufacturing industry

Table 1.
Keyword string

Keyword String	Scopus	Science Direct
"Lean Ergonomics" AND "Manufacturing Industry"	39	7
Lean AND "Human Factors" AND "Manufacturing Industry"	68	7
Lean AND Ergonomics OR "Human factors" AND "Manufacturing industry"	31	44
Total	196	
Duplication	58	
Irrelevant	86	
Article exclusion	34	

Table 2.
Inclusion and exclusion criteria

Criteria	Description
Inclusion	All review articles within the last 5 years (2019-2023) Relevant to the study topic Written in English
Exclusion	Non relevant to the topic (Wrong intervention) Only discussing lean or ergonomics only (Wrong Study Design) Not a manufacturing industry (Wrong Setting) Full text cannot be accessed (not open access)

The need for experimental confirmation regarding the tendency of positive and negative impacts, as well as determining the causes of differences in results due to Lean Manufacturing, on human factors (ergonomics) will be a significant contribution [8]. And having more examinations related towards the implementation of lean ergonomics can encourage companies to be responsible in making decisions to design and improve processes in the workplace. It is recommended that the implementation of activities or workplace scenarios that may endanger employees' ergonomic well-being, whether due to the nature of their physical surroundings, the tasks they perform, or recognized psychological and social pressures, should be given precedence [9].

Apart from that, validation needs to be carried out in additional manufacturing and service industries simultaneously, by selecting the right analysis tools. And one possible solution is to pilot Lean tools with more specific ergonomic analysis methods [10]. This aligns with the findings of previous research, which suggests the need for a research approach to industrial setups that combine human-operated, machine-driven, and computerized workflows, and the recommended strategy (procedure, device) will be considered robust, as it has been examined and proven effective in sophisticated operations of firms active in practical economic conditions [11].

Based on the perseverance of the study above, several research questions (QR) were built from this systematic literature review, namely:

- QR1: How has the Lean Ergonomic studies developed in the last 5 years?
- QR2: What impacts have been reported in the existing Lean Ergonomic studies?
- QR3: What are the limitations and challenges of Lean Ergonomics studies?
- QR4: What opportunities exist for the future development of Lean Ergonomics studies?

2.2. *Research flow*

This study focuses on the implementation of lean ergonomics and its impact on the manufacturing industry. The evaluation covers the concepts, methods, and tools used in implementation, as well as the impacts and opportunities for further research. This paper employs a Systematic Literature Review (SLR) methodology, utilizing academic databases such as Scopus via ScienceDirect and Publish or Perish. Using a comprehensive search strategy that combines keywords and synonyms—including *Lean*, *Ergonomics*, *Human Factors*, and *Manufacturing Industry*—196 potentially relevant articles were identified (Table 1). The search was limited to articles published between 2019 and 2023 (with the search completed on November 15, 2023) in the field of Engineering studies.

The filtering stage began with the removal of duplicate articles, resulting in the identification of 58 duplicates (56 detected by the system and 2 identified manually). After the duplication filtering stage, the process continued with screening the titles and abstracts of the remaining articles using predetermined inclusion and exclusion criteria. The inclusion criteria were as follows: (1) the study focuses on the implementation of lean and ergonomic concepts in the production sector; (2) the research reports on the impacts, methods, tools, challenges, and opportunities of implementing lean ergonomics; and (3) the research is written in English. Articles were excluded if they: (1) failed to meet the specified selection criteria; or (2) lacked accessible, complete documentation (Table 2). Following the title and abstract screening stage, 86 articles were deemed irrelevant to the study criteria.

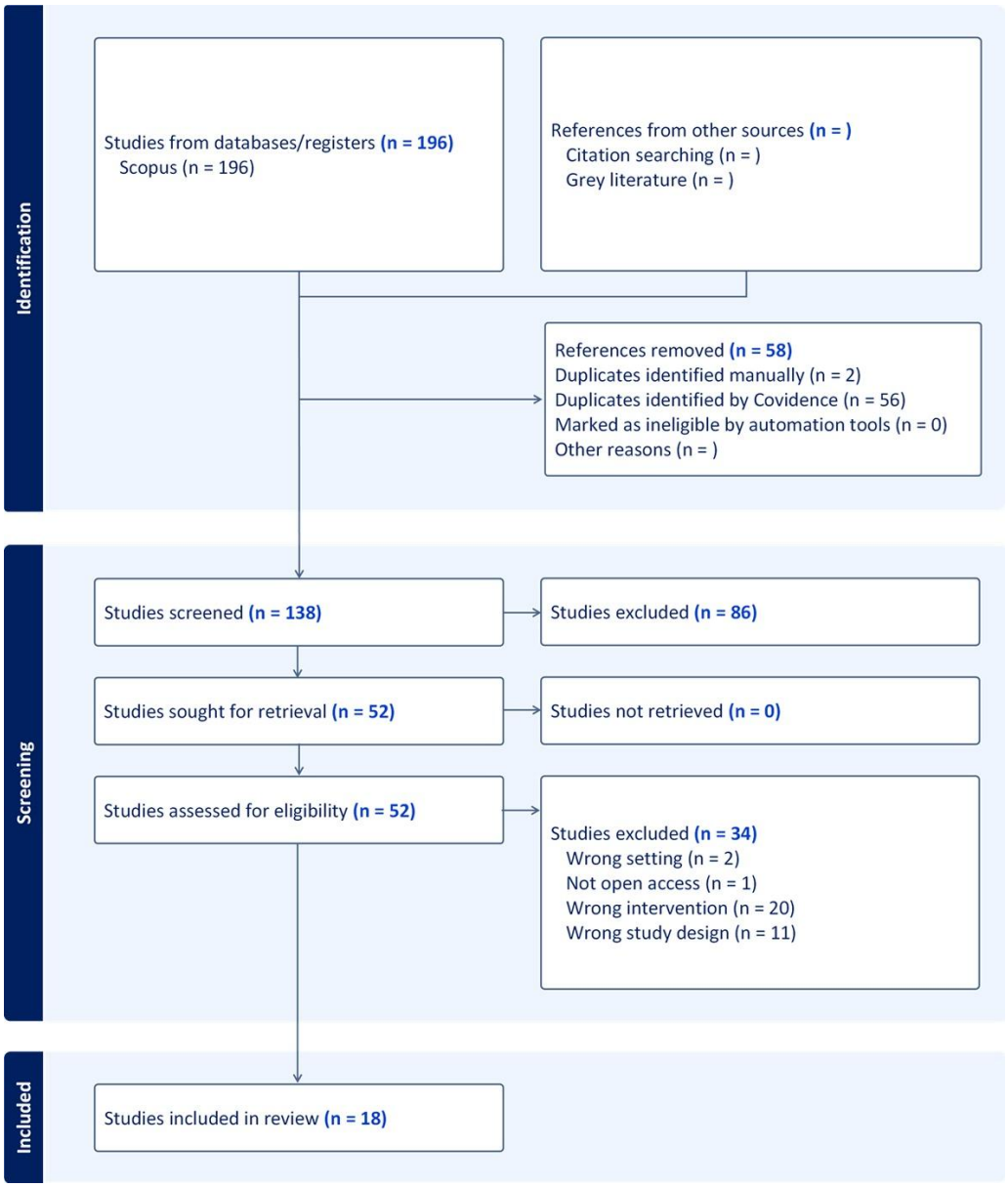

Figure 3. Prisma flowchart

The next filtering is full text screening, where the full text assessment of records that pass the screening stage uses the same inclusion and exclusion criteria. From the results of the full text screening, 34 articles were obtained that met the exclusion criteria, and as a result, 18 articles were obtained that were relevant and in accordance with the topic of discussion that would be included in the discussion of the study and analysis of the literature. The following is the filtering process using the Prisma method as previously explained (Fig. 3).

3. Results and discussions

The next step involved extracting data from the selected studies (18 articles) using standardized tables. The tables included the following information: (1) bibliographic details (author, year, title, journal); (2) study characteristics (country, industry, description, and sample size); (3) lean and ergonomic methods and tools used (e.g., value stream mapping, 5S, JIT, ergonomic risk assessment, etc.); (4) the impact of implementing lean ergonomics (e.g., productivity, quality, safety, health, satisfaction, etc.); and (5) limitations, challenges, and opportunities of lean ergonomic integration studies (e.g., organizational culture, management support, employee involvement, training, etc.).

3.1. Development of lean ergonomic studies in the manufacturing industry

Fig. 4 shows the results of article classification based on country, year, research methods and case study method. Fig. 4 (a) shows the distribution of studies based on the researcher's country of origin, where the most articles come from Portugal, that is 6 articles (33.33%), followed by researchers from India, 3 articles (16.67%), from South Africa with 2 articles (11.11%), and the remaining 1 article each from Serbia, Spain, China, Poland, Ethiopia, New Zealand and Denmark.

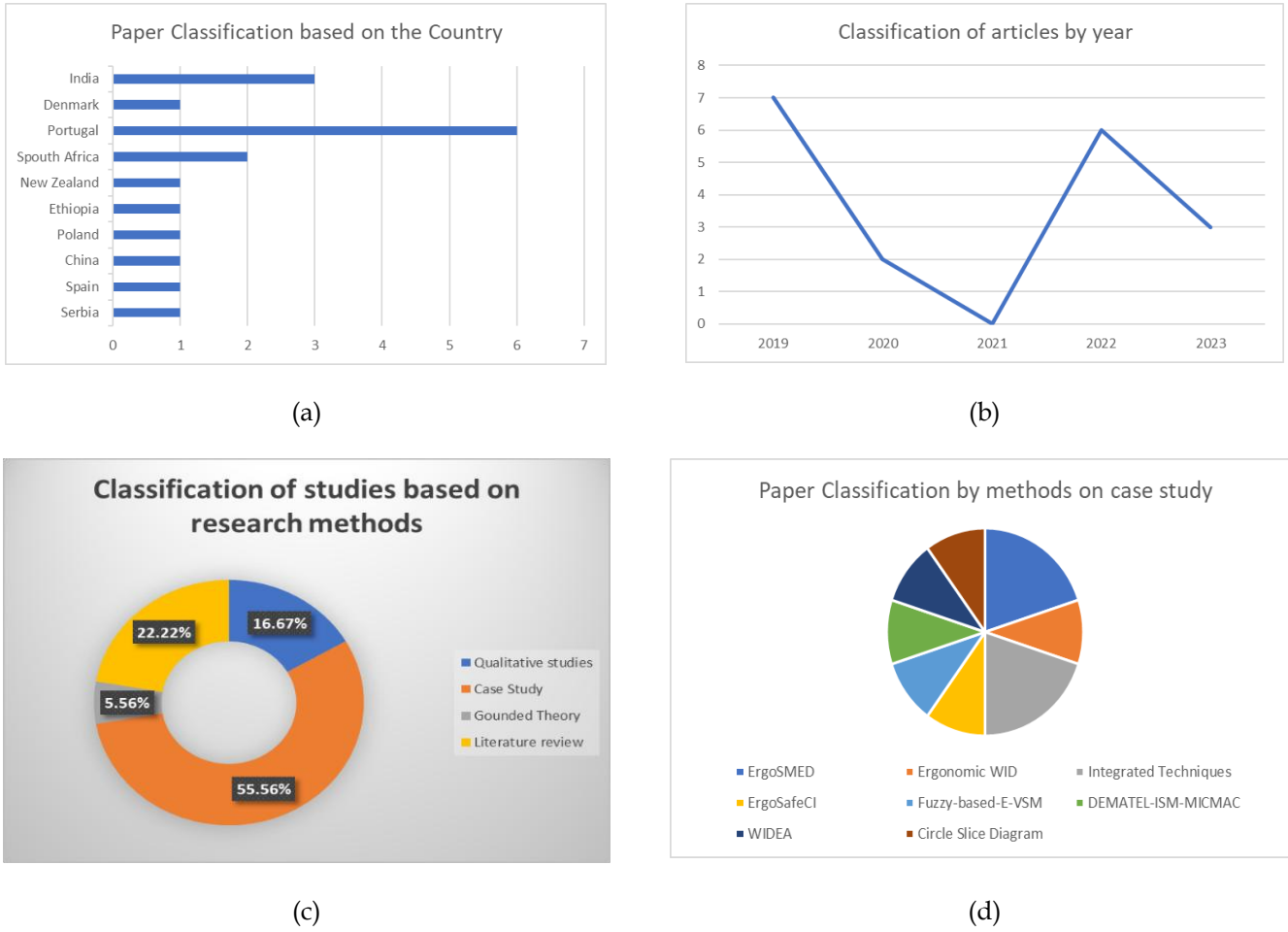

Figure 4. Classification of articles based on (a) country, (b) year, (c) research study method, and (d) case study methods/tools

The articles were categorized by year of publication (Fig. 4(b)). It can be seen that the highest number of publications occurred in 2019, with 7 articles (38.89%), followed by 2022 with 6 articles (33.33%), and 2023 with 3 articles (16.67%). In 2020, 2 articles were identified (4.16%), while no related articles were published in 2021. The classification by methodology provides a comprehensive overview of the approaches used in the collected research articles (Fig. 4(c)). Visually, the chart divides the number of articles into four segments, each representing a different methodology: Systematic Literature Review (SLR), qualitative research, grounded theory, and case studies. The largest portion, at 53.33%, represents case studies, followed by SLR articles at 22.22%, qualitative research at 16.67%, and grounded theory with 1 article (5.56%).

Meanwhile, the classification of tools used in case studies is illustrated in Fig. 4(d). A total of 8 methods/tools were identified across 10 case study articles. The ErgoSMED tool was used in 2 articles (20%), as were integration tools. The remaining tools—Ergonomic WID, ErgoSafeCI, WIDEA, Fuzzy-based E-VSM, Circle Slice Diagram, and DEMATEL-ISM-MICMAC—were each used in 1 article.

Lean and ergonomic systems represent different priorities, often requiring careful consideration of trade-offs. Lean methodology focuses on eliminating waste, reducing costs, and maximizing efficiency. This is achieved by defining value from the customer's perspective, mapping process flows, eliminating non-value-adding steps, and making continuous improvements. However, an exclusive focus on efficiency can overlook human factors. In contrast, ergonomic design prioritizes adapting equipment, tasks, and processes to align with the user's abilities and limitations. It emphasizes optimizing comfort, safety, accessibility, and the overall human experience. However, a sole focus on ergonomics can introduce additional costs and complexity, potentially offering little added value from a lean perspective.

Lean systems and ergonomics are two distinct approaches to managing work processes and worker well-being. Lean systems aim to enhance efficiency and streamline manufacturing operations by identifying and removing non-essential activities that do not contribute to the final product's value. This approach prioritizes improving output efficiency by focusing on tasks that directly enhance productivity while systematically eliminating unnecessary processes that consume resources without adding meaningful value. While lean systems can positively impact workers by increasing productivity and work efficiency, they can

also have negative consequences. For instance, overemphasis on lean thinking may oversimplify processes and neglect worker welfare. Employees may feel pressured to work faster and more efficiently, leading to increased stress.

On the other hand, ergonomics aims to improve the physiological and mental well-being of employees by designing workplaces that align with human characteristics. Its core principle is to adapt tasks, equipment, and work environments to human capabilities and limitations. Like lean, ergonomics has positive impacts, such as increased worker comfort and safety, reduced injury risks, and lower stress levels. However, focusing exclusively on ergonomics can reduce production efficiency, as it may require changes in design or work processes that conflict with lean principles.

3.2. *The impact of implementing lean ergonomics in industry*

Trade-offs between these two approaches is important. Too much focus on efficiency without paying attention to worker well-being can have a negative impact on long-term productivity. On the other hand, too much focus on ergonomics without paying attention to efficiency can hinder business growth. Therefore, a balanced approach is necessary to achieve optimal results for companies and workers. Example of specific trade-offs that may arise in implementing lean and ergonomics from existing studies:

1) Lean initiatives that focus on reducing cycle times can lead to increased worker fatigue and musculoskeletal disorders. For example, if workers are required to perform tasks at a faster pace, they are more likely to experience muscle strain or pain [12].
2) Ergonomic interventions that prioritize worker comfort may require additional equipment or training, which can be considered wasteful from a lean perspective. For example, installing adjustable workstations or providing ergonomics training may initially increase costs, but these investments can ultimately increase worker productivity and reduce absenteeism rates. Many industrial managers still consider ergonomics a cost rather than an investment [13].

Previously, research revealed that the introduction of lean practices led to heightened tensions and disagreements among team members tasked with driving the lean transition. This finding suggests unintended social consequences of lean implementation. Additionally, a subsequent study by also uncovered evidence that lean practices can adversely affect workplace health and safety. Specifically, their research indicated that lean implementation resulted in ergonomic issues such as sitting discomfort, as well as increased noise levels and heat exposure for workers [14].

Sociotechnical study trends related to the impact of Lean on worker health over a span of 20 years (1990–2013) have extensively revealed mixed outcomes from Lean implementation, which vary based on specific practices and industry sectors. Approximately 35% of studies reported both positive and negative effects, while over half of the research indicated that lean implementation negatively impacted worker health. The analysis highlighted that Just-In-Time (JIT), a core lean practice, often led to detrimental consequences. These included increased time pressure, insufficient recovery periods, expanded work areas, and heavier workloads. Such changes adversely affect workers' physical well-being, manifesting in cumulative trauma disorders and musculoskeletal issues. Moreover, these factors also took a toll on employees' mental health [15].

The adoption of lean principles in manufacturing environments has been found to have detrimental effects on worker health and safety, primarily due to insufficient attention to social factors. A comprehensive review of research in this area revealed troubling findings: 75% of studies reported adverse consequences of lean implementation. These negative impacts manifested in various forms, including increased worker fatigue, a rise in repetitive and monotonous tasks, significantly heavier workloads, and elevated levels of mental stress among employees [16].

Based on 18 articles that meet the inclusion criteria for the lean implementation study, which was evaluated from the ergonomic aspect, it was found that many industrial executives consider ergonomics only to be an instrument used to prevent health and disease, and not as a technique to save costs or reduce waste [13]. A literature review was carried out by [14] found that research related to the effect of lean principles on workplace safety and employee wellbeing was examined in the RMG industry, some show positive relationship such as: workers feel more suited to their jobs, and helps reduce fatigue and human energy by shortening distances, while there are also studies that find negative impacts after implementation, that are sitting discomfort, noise and heat.

Ergonomics is one of the main studies that should be integrated with lean manufacturing principles. Building workplaces that adhere to Lean and Ergonomics values marks in improved productivity for employees and the Company [13]. Initial studies stated that lean manufacturing practices often had detrimental effects on the health of workers in manual assembly roles. However, more recent research indicates a shift in this trend. While some negative impacts persist, there's growing evidence of positive outcomes for worker health as lean methodologies have evolved and been refined in assembly environments [14]. Here are the positive impacts of implementing Lean ergonomics mentioned in the extraction (Table 3).

Table 3.
The impact of lean ergonomic in the manufacturing industry

Work System Element	Impact of implementation lean ergonomics	References
Improving Working Conditions	Improving working conditions	[17]
	Reducing variability in work methods	[18]
	Reducing task duration	[19]
	Reducing waste, minimizing travel distance and transfer time	[20]
	Preventing waste	[21]
	Increasing efficiency and effectiveness of the workplace	[21]
	Reducing time spent searching for production tools	[20]
	Improving process design	[21]
	Manufacturing flexibility	[22]
	Helping to develop a human-centered workplace	[23]
Worker Welfare	Improving worker welfare	[22]
	Enhancing worker performance	[24], [25]
	Worker safety and health	[22], [24]
	Improving safe/ergonomic behavior of workers	[26], [27]
Quality	Enhancing quality control	[18]
	Reducing quality rejection	[28]
	Minimizing rework	[29]
	Minimizing waste	[26], [30], [31]
	Minimizing product defects	[24]
Efficiency	Reducing downtime	[20], [27]
	Reducing waiting time	[24]
	Reducing machine setup time	[17], [26]
	Reducing resource consumption	[24], [31]
	Improving production line efficiency	[20]
	Enhancing raw material circulation	[31]
Productivity	Increasing work productivity	[17], [26], [28], [32]
Sustainability	Supporting sustainability principles	[25]

3.3. Limitations and challenges of lean ergonomic studies

Regarding the limitations and challenges of studying Lean Ergonomics in the manufacturing industry, what can be used as further research opportunities in the future are as follows:

- The research conducted was primarily a single case, indicating the need for further empirical research to generalize biases that are common in the industry [33].
- It was also stated in one of the previous studies that the limitations of the research which was only focused mainly on the upper management level, required input from lower levels, such as factory employees, because this could provide more in-depth information about RFP in the workplace [34].
- The challenge that can cause poor implementation of E-HRM practices is a lack of management concentration [35].
- There are studies that evaluate lean ergonomics only on one production layout and without considering safety, chemical effects and environmental factors [16].
- The important to validate lean ergonomic tools such as ErgoSafeCI tool throughout manufacturing and non-manufacturing segments simultaneously [36].
- Analysis of surveys among industry executives shows that many still perceive ergonomics primarily as a tool for safeguarding worker health and averting illnesses, rather than recognizing its potential as a strategy to enhance efficiency and minimize waste [37].
- There's a reciprocal relationship between ergonomic hazards and inefficiencies in Lean manufacturing. Poor ergonomics can result in the types of waste that Lean principles aim to eliminate, while suboptimal Lean practices may introduce ergonomic risks. This interconnection underscores the close alignment between workplace ergonomics and Lean manufacturing methodologies, suggesting that improvements in one area often yield benefits in the other [10].

In conclusion, case studies are not comprehensive, lack of understanding from various levels of the workplace, neglect of specific elements in the analysis, difficulty in getting support from management, and the need for validation of tools, are some of the common weaknesses found in previous research, so this is an opportunity to carry out further research with a wider scope.

3.4. Opportunities for future lean ergonomic studies

Future research should focus on the validation of tools that can be used to assess the effectiveness of Lean practices in improving worker health and safety across a range of industry sectors. The need to validate these tools arises from the unique characteristics of each sector, which may affect the success of Lean implementation. As a result, there is a requirement for broader and more diverse research initiatives to create

appropriate tools tailored to the specific contexts of different industries.

Conducting case studies in sectors such as manufacturing, healthcare, and construction could help kick off this process. Researchers can gain insights into the variations in Lean implementation and how these variations influence worker health by engaging with multiple industries. From this, we will learn how evaluation tools can be adapted to meet the different needs of each sector. For example, the manufacturing industry might require more attention to ergonomic hazards related to repetitive work, while the healthcare sector may necessitate a greater emphasis on mental and physical workload considerations.

Moreover, there is a pressing need for the development and validation of comprehensive assessment tools capable of measuring the effects of Lean practices on worker health and safety. These tools must encompass all ergonomic aspects and health and safety metrics, combined with employee feedback. Incorporating these elements will enable the metrics to provide a complete view of the impact of Lean practices.

These tools should be developed and validated through a collaborative approach that involves management, Lean experts, ergonomics specialists, and workers. Engaging a diverse range of stakeholders in the research process leads to the creation of tools that address relevant field needs, thereby increasing their applicability and relevance. In research, while we strive to create innovative solutions, it is essential to engage the right people to ensure that our efforts truly matter. This collaborative approach not only helps to ensure the robustness of the tools but also fosters their adoption across diverse industry sectors.

The integrated assessment tools developed through this study require further research, particularly regarding the process of their validation across various industries. The tools created while exploring this subject area will undoubtedly contribute to and serve any organization seeking to implement and enhance Lean practices while prioritizing the health and safety of their workforce.

4. Conclusions

From the existing discussion, it is realized that Lean systems and Ergonomics as two distinct approaches to the working process and the workers. The lean system strives to remove the waste in the manufacturing process and reduce their occurrences, whereas ergonomics is concerned with optimization of human characteristics through designing environment that suits them. While excessive focus on efficiency at the cost of workers' health and safety is detrimental for long-term organizational efficiency, an exaggerated emphasis on ergonomics as an essential organizational and business value can act as a drawback for business development. Thus, it is important to find a middle ground to enable employers to report better results, while at the same time ensuring that workers are also benefiting from it.

Research by various authors indicates that properly integrating lean principles with ergonomics can yield numerous benefits, including enhanced productivity, cost reduction, shorter wait times, quality improvements, operational efficiency gains, and better worker health, safety, and performance. However, some studies also note potential short-term negative impacts on occupational health and safety, though evidence is limited. To mitigate these risks, careful assessment and adjustment of lean ergonomics implementation is crucial. There's also a need for further research, particularly in developing integrated assessment tools with standard guidelines, to prevent increased workload or repetitive stress from lean tools. Overall, it is hoped that strategic integration of lean and ergonomics can minimize negative effects while maximizing benefits.

In many surveys, lean and ergonomics have been regarded as commendable approaches in work system redesign. As can be seen from the outcome, the efficiency and performance of the systems are enhanced in productivity while the welfare of the workers is also enhanced. However, currently, there is only a limited amount of research in this respect and integration tools that are also developed, also must be further tested in various sectors of industry.

Declaration statement

Nofirza: **Conceptualization, Methodology, Project administration, Resources, Software, Visualization, Writing - Original Draft, Writing - Review and Editing**. Rika Ampuh Hadiguna: **Conceptualization, Writing - Review, Formal Analysis, Supervision and Validation**. Elita Amrina: **Conceptualization, Writing - Review, Formal Analysis, Supervision and Validation**.

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Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

The data that support the findings of this study are available from the author, corresponding author, upon reasonable request.

AI Usage Statement

Generative AI and AI-assisted tools were used to enhance the language and readability of this manuscript. The authors have reviewed and revised all AI-generated content to ensure its accuracy and alignment with the research. The authors remain fully responsible for the work's scientific content, conclusions, and integrity, and disclose the use of AI to ensure transparency and adherence to publisher guidelines.

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