PAPER – OPEN ACCESS

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Author : Listiani Nurul Huda, et al
DOI : 10.32734/ee.v9i2.2829
Electronic ISSN : 2654-704X
Print ISSN : 2654-7031

Volume 9 Issue 2 – 2026 TALENTA Conference Series: Energy & Engineering (EE)

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EE Conference Series 09 (2026)
TALENTA Conference Series
Available online at https://talentaconfseries.usu.ac.id

Sustainable and Lean Strategy for Efficient Product Design in Ergonomic Views

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Abstrak

Integrasi antara *sustainability*, *lean manufacturing*, dan ergonomi menjadi semakin penting dalam desain produk modern akibat persaingan industri global, meningkatnya perhatian terhadap lingkungan, serta kesadaran konsumen terhadap kualitas produk dan kesejahteraan pekerja. Paper ini membahas strategi *sustainable* dan *lean* untuk desain produk yang efisien dari sudut pandang ergonomi. Penelitian ini mengeksplorasi bagaimana prinsip-prinsip ergonomi berkontribusi terhadap efisiensi produk, pengurangan pemborosan, keselamatan kerja, kepuasan pelanggan, dan keberlanjutan lingkungan. Metode yang digunakan adalah pendekatan kualitatif melalui studi literatur dengan meninjau berbagai penelitian terbaru terkait *sustainable manufacturing*, *lean product development*, *ergonomic engineering*, *Industry 4.0*, dan *human-centered design*. Hasil penelitian menunjukkan bahwa integrasi ergonomi dalam pengembangan produk yang *sustainable* dan *lean* mampu meningkatkan efisiensi operasional, mengurangi risiko muskuloskeletal, meminimalkan limbah material, meningkatkan efisiensi energi, serta meningkatkan *usability* produk. Selain itu, teknologi digital seperti *smart manufacturing*, *artificial intelligence*, *digital twin*, dan sistem *monitoring* berbasis *Internet of Things* (IoT) mendukung optimalisasi ergonomi dan pengelolaan siklus hidup produk secara berkelanjutan.

Kata Kunci: Desain berkesinambungan; Desain produk; Ergonomi; *Industry 4.0*; Strategi *lean*

Abstract

The integration of sustainability, lean manufacturing, and ergonomics has become increasingly important in modern product design due to global industrial competition, environmental concerns, and increasing consumer awareness regarding product quality and worker well-being. This paper discusses sustainable and lean strategies for efficient product design from ergonomic perspectives. The study explores how ergonomic principles contribute to product efficiency, waste reduction, worker safety, customer satisfaction, and environmental sustainability. A qualitative literature review approach was applied by examining recent studies related to sustainable manufacturing, lean product development, ergonomic engineering, Industry 4.0, and human-centered design. The findings indicate that integrating ergonomics into lean and sustainable product development improves operational efficiency, reduces musculoskeletal risks, minimizes material waste, enhances energy efficiency, and increases product usability. Furthermore, digital technologies such as smart manufacturing, artificial intelligence, digital twins, and IoT-based monitoring systems support ergonomic optimization and sustainable product lifecycle management. The study concludes that ergonomic-based sustainable lean strategies provide long-term benefits for industries through productivity improvement, cost reduction, environmental preservation, and improved human well-being.

Keywords: *Ergonomics*; *Industry 4.0*; *Lean strategy*; *Product design*; *Sustainable design*

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Selection and peer-review under responsibility of The 9th National Conference on Industrial Engineering (NCIE) 2026
p-ISSN: et al, e-ISSN: 2654-7031, DOI: 10.32734/ee.v9i1.2829

1. Introduction

Global industrial development has encouraged companies to develop products that are efficient, environmentally friendly, cost-effective, and user-oriented [7], [55]. Manufacturing industries are currently facing increasing pressure to minimize production costs while maintaining high-quality products and sustainability standards [44]. In this context, sustainable and lean strategies have emerged as essential approaches for efficient product development.

Sustainable product design focuses on minimizing environmental impacts throughout the product lifecycle, including material selection, energy consumption, production processes, transportation, usage, and disposal [61]. Meanwhile, lean strategy emphasizes waste elimination, continuous improvement, value creation, and operational efficiency. However, many organizations still overlook ergonomic considerations during product development and manufacturing system design [29].

Ergonomics plays an important role in ensuring that products, systems, and work environments fit human capabilities and limitations. Poor ergonomic design can lead to worker fatigue, musculoskeletal disorders, low productivity, increased operational costs, and customer dissatisfaction. Therefore, integrating ergonomic principles into sustainable and lean strategies becomes highly important for achieving efficient product design. Modern industrial systems supported by Industry 4.0 technologies have significantly transformed manufacturing processes [10], [46]. Smart factories, digital twins, wearable sensors, artificial intelligence, and IoT-based systems enable industries to improve ergonomics and sustainability simultaneously [30], [35]. Human-centered product development is now becoming a key competitive advantage in global markets [51]. This paper aims to discuss sustainable and lean strategies for efficient product design from ergonomic perspectives. The study also highlights recent technological developments and practical applications in manufacturing industries.

2. Literature Review

2.1. Sustainable Product Design

Sustainable product design refers to the development of products that minimize negative environmental impacts while maximizing economic and social benefits. Sustainable design considers the entire product lifecycle, including raw material extraction, manufacturing, transportation, use phase, maintenance, and disposal. Several important principles of sustainable design include:

- Reduction of material waste
- Energy-efficient manufacturing processes
- Use of recyclable and eco-friendly materials
- Product durability and modularity
- Reduction of carbon emissions
- Circular economy implementation

The circular economy concept encourages industries to design products that can be reused, repaired, remanufactured, or recycled. This approach reduces resource depletion and environmental pollution [57].

2.2. Lean Strategy in Product Design

Lean strategy originated from the Toyota Production System (TPS) and focuses on eliminating non-value-added activities. Lean principles improve operational efficiency by reducing waste, shortening production lead times, and enhancing quality.

Lean manufacturing identifies seven major types of waste that can reduce efficiency and productivity within a production process. These wastes include overproduction, which occurs when goods are produced in excess or before they are needed, and waiting time, where delays happen due to idle workers, machines, or materials. Transportation waste refers to the unnecessary movement of materials or products, while overprocessing involves performing more work or using more resources than required. Excess inventory is another form of waste, resulting from storing more materials or products than necessary. In addition, unnecessary motion includes inefficient movements by workers or equipment that do not add value to the process. Lastly, defects represent errors or faulty products that require rework or replacement, leading to additional time and cost. Lean product design integrates customer value, continuous improvement (Kaizen), Just-In-Time (JIT), and value stream mapping to optimize manufacturing processes.

2.3. Ergonomics in Product Design

Ergonomics is the scientific discipline concerned with understanding human interactions with systems and products [19]. Ergonomic design aims to optimize human well-being and system performance. There are three major ergonomic domains:

- Physical Ergonomics: Focuses on human anatomy, posture, biomechanics, repetitive movements, and musculoskeletal disorders.

- Cognitive Ergonomics: Related to mental workload, decision-making, user interfaces, human-computer interaction, and cognitive performance.
- Organizational Ergonomics: Deals with work systems, teamwork, communication, job design, and organizational structures. Ergonomic product design improves usability, comfort, safety, productivity, and customer satisfaction (ISO 6385, 2016).

2.4. Integration of Sustainability, Lean, and Ergonomics

The integration of sustainability, lean practices, and ergonomics creates a holistic approach to improving manufacturing efficiency. Sustainable lean ergonomics focuses on optimizing resource utilization while simultaneously protecting workers and enhancing product usability. By combining these three concepts, industries can achieve more efficient, safe, and environmentally responsible production systems.

This integration offers several important benefits, including reduced material and energy waste, which helps improve resource efficiency and environmental performance. The approach also lowers occupational injury risks by creating safer and more ergonomic working conditions for employees. In addition, worker productivity can be improved through more efficient processes and better workplace design [58].

Furthermore, the integration contributes to better product quality and enhances customer experience by ensuring products are more reliable, functional, and user-friendly. Organizations can also benefit from reduced operational costs due to minimized waste and improved efficiency. Ultimately, the integration supports increased environmental sustainability and promotes long-term industrial competitiveness [58].

3. Research Methodology

This research adopted a Systematic Literature Review (SLR) methodology to investigate how sustainability, lean principles, and ergonomics can be integrated into product design practices. The SLR approach was chosen due to its ability to provide a rigorous, systematic, and transparent process for reviewing and selecting relevant literature, thereby enhancing the reliability and reproducibility of the findings. Through this method, the study aimed to collect, assess, and consolidate existing research on sustainable manufacturing, lean product development, ergonomic considerations, and the application of Industry 4.0 technologies.

The literature search was conducted using several scientific databases, including Scopus, ScienceDirect, SpringerLink, and Google Scholar, to obtain relevant and high-quality publications. The search process used combinations of several keywords related to the research topic, including “sustainable product design,” “lean manufacturing,” “ergonomics,” “human-centered manufacturing,” “Industry 4.0,” and “sustainable lean ergonomics.” Boolean operators such as AND and OR were applied to improve the accuracy and relevance of the search results. An example of the search query used in this study was:

(“sustainable design” AND “lean manufacturing” AND “ergonomics”) OR (“Industry 4.0” AND “human-centered manufacturing”)

The literature selection process was performed using predetermined inclusion and exclusion criteria. The inclusion criteria consisted of peer-reviewed journal articles and conference proceedings published between 2017 and 2026, written in English, and specifically discussing topics related to sustainability, lean practices, ergonomics, product design, and Industry 4.0 implementation in manufacturing environments. Meanwhile, duplicate articles, non-peer-reviewed publications, studies unrelated to manufacturing systems or product design, and articles with insufficient information were excluded from the analysis.

The literature selection process was conducted using a structured approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The procedure involved several stages, including database searching, removal of duplicate records, screening of titles and abstracts, evaluation of full-text articles, and the final inclusion of relevant studies. The initial search yielded 165 publications from the selected databases. Following the elimination of duplicates, 142 articles proceeded to the screening stage. The title and abstract review further narrowed the pool to 87 potentially relevant studies. After conducting a comprehensive full-text evaluation, 63 articles were retained for in-depth analysis.

The selected literature was analyzed using a qualitative thematic analysis approach. The reviewed studies were classified into several themes, including sustainable product design, lean strategy implementation, ergonomic applications, Industry 4.0 technologies, and integrated sustainable lean ergonomic practices. The findings were then compared and synthesized to identify common patterns, relationships, implementation challenges, and future opportunities associated with efficient product design from ergonomic perspectives.

4. Discussion

4.1. Sustainable and Lean Product Design Framework

Efficient product design requires the balanced integration of sustainability principles, lean strategies, and ergonomic considerations. Rather than functioning independently, these concepts interact with one another to create a comprehensive framework that supports manufacturing performance and product value creation. Sustainable product design focuses on minimizing environmental impacts throughout the product lifecycle, including material selection, manufacturing processes, transportation, use, and disposal [54]. Meanwhile, lean strategy emphasizes waste elimination, continuous improvement, and operational efficiency.

The proposed framework begins with customer requirement identification, followed by sustainable material selection, lean process implementation, ergonomic design integration, and technological support through Industry 4.0 systems. The implementation of eco-friendly materials, recycled components, and modular design approaches contributes to reducing environmental impacts while supporting product flexibility and lifecycle management [25], [54], [32].

Lean principles such as value stream mapping, Just-In-Time production, and continuous improvement further strengthen manufacturing performance by reducing unnecessary activities and increasing operational efficiency [43]. In addition, ergonomic integration supports the development of products and manufacturing systems that are aligned with human capabilities and limitations, thereby improving usability and operational effectiveness [53], [60].

4.2. Ergonomic Views in Efficient Product Design

Ergonomics plays an essential role in improving both manufacturing performance and product efficiency. Previous studies indicate that poor ergonomic conditions can negatively affect operational performance through increased worker fatigue, musculoskeletal disorders, human errors, and reduced productivity [29], [35].

Physical ergonomics primarily contributes through improvements in workstation design, posture optimization, ergonomic tools, and the reduction of repetitive movements. Various interventions such as adjustable workstations, ergonomic seating systems, and human–robot collaboration have demonstrated significant improvements in worker comfort and productivity while reducing injury risks [41], [47].

Cognitive ergonomics has become increasingly important in Industry 4.0 environments where workers interact with digital technologies and intelligent systems. Smart interfaces, digital dashboards, augmented reality systems, and wearable devices enable workers to process information more effectively and support decision-making processes [17].

In addition, organizational ergonomics contributes to sustainable manufacturing performance through effective communication systems, teamwork practices, and flexible work structures that improve collaboration and safety culture. These findings indicate that ergonomics should not be considered solely as a workplace safety initiative but also as a strategic factor that contributes directly to operational effectiveness and long-term sustainability.

4.3. Lean Ergonomics and Waste Reduction

Recent journal studies indicate that ergonomic improvements significantly support lean manufacturing implementation by reducing unnecessary motion, worker fatigue, defects, and operational waste. Ergonomic interventions positively influence lean manufacturing performance because better workstation design reduces physical strain and increases productivity. Furthermore, ergonomic optimization contributes to improved quality control and lower production variability.

A systematic review conducted by researchers in ergonomic analysis within lean manufacturing and Industry 4.0 environments explained that Lean Production Systems (LPS) improve manufacturing competitiveness through value creation with fewer resources while emphasizing worker well-being and operational sustainability. The study highlighted that integrating ergonomics into lean systems reduces musculoskeletal disorders, improves employee satisfaction, and increases production efficiency.

Research [8] demonstrated that Industry 4.0 technologies and World Class Manufacturing (WCM) systems can be integrated with ergonomic principles to improve workstation productivity and worker comfort simultaneously. Their findings showed that digital technologies such as sensors, wearable devices, and human-centered automation systems significantly enhance both ergonomic performance and manufacturing efficiency.

Another important study explained that the integration of Industry 4.0 and Lean Manufacturing contributes positively to sustainable manufacturing performance [23]. The study revealed that lean manufacturing acts as a mediating factor between Industry 4.0 implementation and sustainability outcomes.

Ergonomic deficiencies frequently contribute to several categories of lean waste such as unnecessary motion, waiting time, defects, and overprocessing [13]. Several examples demonstrate how poor ergonomic conditions negatively affect industrial performance [29]. Poor workstation layouts can increase unnecessary movement, causing workers to spend more time and energy performing tasks inefficiently [15], [56]. Heavy lifting tasks may increase worker fatigue and injury risks, while complex machine interfaces contribute to higher levels of human error [42].

The reviewed studies collectively indicate that ergonomic interventions contribute to lean performance by reducing unnecessary motion, improving workflow efficiency, lowering defect rates, and minimizing operational waste. Therefore, ergonomics not only improves worker well-being but also strengthens sustainable manufacturing performance [29].

4.4. Synthesis of Sustainable, Lean, and Ergonomic Integration

Based on the reviewed literature, sustainability, lean principles, and ergonomics should be considered as interconnected dimensions rather than isolated concepts. Sustainability primarily focuses on minimizing environmental impacts throughout product lifecycles, while lean practices seek to eliminate non-value-added activities and improve process efficiency. Ergonomics ensures that systems and products are designed according to human capabilities and limitations [5].

The synthesis of previous studies reveals that ergonomics contributes directly to lean performance by reducing operational waste and improving productivity. Furthermore, ergonomic interventions indirectly support sustainability objectives through more efficient resource utilization, lower material consumption, and improved worker well-being [16].

The integration of these concepts creates a comprehensive framework that enables organizations to simultaneously improve productivity, product quality, workplace safety, and environmental sustainability. Consequently, sustainable lean ergonomics can be considered a strategic approach for achieving long-term competitiveness in manufacturing industries [5], [16]. Table 1 presents the relationship between selected ergonomic interventions and their corresponding impacts on lean performance and sustainability outcomes.

Tabel 1. Contribution of Ergonomic Interventions to Lean and Sustainable Manufacturing

Ergonomic intervention	Lean impact	Sustainability impact
Adjustable workstation	Reduced unnecessary motion	Reduced energy consumption
Human-centered interface	Reduced defects	Reduced material waste
Wearable monitoring system	Reduced waiting time	Improved worker well-being
Collaborative robots	Reduced physical workload	Increased process efficiency

The reviewed literature consistently demonstrates that ergonomics serves as an enabling factor that strengthens both lean implementation and sustainable manufacturing performance. The integration of ergonomic principles with sustainability and lean strategies contributes to operational improvements through waste reduction, productivity enhancement, and safer working environments [5], [16].

4.5. Industry 4.0 and Smart Factory Applications

The findings further indicate that Industry 4.0 technologies strengthen sustainable lean ergonomics implementation through data-driven manufacturing systems. Key technologies identified in the literature include Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, wearable sensors, and collaborative robots [30], [18], [36].

Artificial Intelligence systems can support predictive ergonomic assessments through real-time data analysis and risk identification. Digital Twin technology enables virtual testing and simulation of product designs and manufacturing systems before physical implementation. Wearable devices facilitate real-time monitoring of worker posture, fatigue levels, and workload conditions.

The implementation of these technologies reflects a transition from conventional manufacturing systems toward human-centered smart manufacturing environments that balance productivity, sustainability, and worker well-being [30], [35].

4.6. Case Studies of Sustainable Lean Ergonomic Product Design

Various industrial applications demonstrate similar implementation patterns despite differences in products and manufacturing environments. Across automotive, electronics, furniture, and healthcare industries, sustainable lean ergonomic practices consistently contribute to productivity improvement, waste reduction, occupational safety enhancement, and sustainability performance. The following cases illustrate practical examples of these implementations.

Toyota integrates ergonomic workstation design with lean manufacturing to reduce unnecessary movement and worker fatigue [38]. Tesla applies Industry 4.0 technologies, AI-based monitoring systems, and ergonomic automation to reduce physical strain and production waste [62]. IKEA implements modular design and circular economy principles to improve product sustainability and usability. Healthcare equipment manufacturers prioritize ergonomic usability and sustainable materials to improve safety and product performance [16].

Although implementation approaches vary across industries, the literature consistently demonstrates several common outcomes [8], [62], [2]:

- Improved worker productivity,
- Reduced operational waste,
- Lower occupational risks,
- Enhanced product usability,
- Increased sustainability performance.

These findings indicate that sustainable lean ergonomic strategies generate measurable operational benefits across different industrial sectors.

4.7. Challenges and Future Trends

Although the integration of sustainability, lean practices, and ergonomics offers many advantages, several challenges still hinder its effective implementation in industries. One of the major challenges is the high implementation cost, as organizations often need significant investments in technology, equipment, and training programs. In addition, limited ergonomic awareness among managers and employees can reduce the effectiveness of ergonomic initiatives within the workplace.

Resistance to organizational change also becomes a common obstacle, as employees and management may be reluctant to adopt new systems and working methods [20]. Furthermore, technological adaptation difficulties can arise when companies struggle to integrate advanced technologies into existing production systems. Another challenge is the lack of skilled human resources who possess adequate knowledge of sustainability, lean manufacturing, ergonomics, and digital technologies. Lastly, data integration complexity presents difficulties in managing and connecting large amounts of information from different systems and technologies, which can affect decision-making and operational efficiency. Addressing these impediments requires a strategic shift toward governance frameworks that foster transparency and cross-departmental collaboration, ensuring that digital investments align with both workforce capabilities and long-term sustainability objectives.

Future trends including:

- Artificial Intelligence-Based Ergonomics: AI systems can predict ergonomic risks and optimize workstation layouts through real-time analytics and smart monitoring systems.
- Human-Robot Collaboration: Collaborative robots (cobots) assist workers in physically demanding tasks while improving safety and reducing musculoskeletal strain.
- Sustainable Smart Manufacturing: Future factories will focus on renewable energy, carbon neutrality, and digital sustainability [6].
- Personalized Product Design: Advanced manufacturing technologies enable customized ergonomic products based on individual user needs [17].

5. Conclusion

This study examined the integration of sustainability principles, lean strategies, and ergonomics in achieving efficient product design within modern manufacturing environments. Based on the reviewed literature, the findings indicate that these three concepts are strongly interconnected and collectively contribute to improving operational performance and long-term industrial sustainability. Sustainable approaches support environmental responsibility through efficient resource utilization and waste reduction, while lean principles enhance manufacturing performance through the elimination of non-value-added activities and continuous improvement practices. Ergonomics complements these approaches by ensuring that products and systems are designed according to human capabilities and limitations.

The findings further reveal that ergonomic implementation contributes significantly to reducing unnecessary motion, minimizing occupational risks, improving usability, and enhancing productivity. In addition, the integration of Industry 4.0 technologies such as Internet of Things (IoT), Artificial Intelligence (AI), Digital Twin systems, wearable technologies, and collaborative robots strengthens sustainable lean ergonomics through real-time monitoring, predictive analysis, and data-driven decision-making. These technologies support the development of more adaptive, efficient, and human-centered manufacturing systems.

From a theoretical perspective, this study contributes by providing an integrated framework that combines sustainability, lean manufacturing, and ergonomic principles within efficient product design. From a practical perspective, the findings can serve as guidance for manufacturing industries in implementing human-centered and sustainable product development strategies aimed at improving productivity, reducing operational costs, and enhancing environmental performance.

However, this study is limited by its reliance on literature-based analysis without empirical validation through industrial case studies or quantitative assessment methods. Therefore, future studies are recommended to validate the proposed framework through real industrial applications, comparative case studies, and quantitative approaches involving performance measurements and ergonomic indicators. Further research may also explore the implementation of emerging technologies within Industry 5.0 environments to support more intelligent and sustainable manufacturing systems.

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