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THE ROLE OF LEAN MANUFACTURING IN ENHANCING OPERATIONAL EFFICIENCY AND WASTE REDUCTION

PERAN LEAN MANUFACTURING DALAM MENINGKATKAN EFISIENSI OPERASIONAL DAN PENGURANGAN LIMBAH

Degdo Suprayitno
Institut Ilmu Sosial Dan Manajemen STIAMI
*degdo.suprayitno@stiami.ac.id

**Corresponding Author*

ABSTRACT
The application of Lean Manufacturing has long been recognized as an effective method for increasing operational efficiency and reducing waste in the manufacturing industry. However, in production environments with high variability, there is still a gap in understanding the role of digital technology integration, such as Artificial Intelligence (AI) and the Internet of Things (IoT), in strengthening Lean implementation. This research aims to explore the impact of integrating AI and IoT within a Lean Manufacturing framework on operational efficiency and waste reduction, especially in diverse production conditions. Using a systematic literature review approach with the PRISMA method, data was collected from various international databases, including Scopus and IEEE Xplore. The research results show that the integration of AI and IoT can improve real-time error detection, minimize downtime, and optimize resource utilization more efficiently. These findings provide practical implications for industries facing high variability to adopt digital technologies to strengthen Lean strategies and drive sustainable competitiveness.
Keywords: Lean Manufacturing, Artificial Intelligence, Internet of Things, Operational Efficiency, Waste Reduction, High Variability

ABSTRAK
Penerapan Lean Manufacturing telah lama diakui sebagai metode efektif untuk meningkatkan efisiensi operasional dan mengurangi limbah dalam industri manufaktur. Namun, dalam lingkungan produksi dengan variabilitas tinggi, masih terdapat celah dalam memahami peran integrasi teknologi digital, seperti Artificial Intelligence (AI) dan Internet of Things (IoT), dalam memperkuat penerapan Lean. Penelitian ini bertujuan untuk mengeksplorasi dampak integrasi AI dan IoT dalam kerangka Lean Manufacturing terhadap efisiensi operasional dan pengurangan limbah, khususnya pada kondisi produksi yang beragam. Menggunakan pendekatan systematic literature review dengan metode PRISMA, data dikumpulkan dari berbagai database internasional, termasuk Scopus dan IEEE Xplore. Hasil penelitian menunjukkan bahwa integrasi AI dan IoT mampu meningkatkan deteksi kesalahan secara real-time, meminimalkan downtime, serta mengoptimalkan pemanfaatan sumber daya secara lebih efisien. Temuan ini memberikan implikasi praktis bagi industri yang menghadapi variabilitas tinggi untuk mengadopsi teknologi digital guna memperkuat strategi Lean dan mendorong daya saing yang berkelanjutan.
Kata Kunci: Lean Manufacturing, Artificial Intelligence, Internet of Things, Efisiensi Operasional, Pengurangan Limbah, Variabilitas Tinggi

1. Introduction

Lean Manufacturing is an important approach in modern industry that focuses on reducing waste and increasing efficiency throughout the production process. Starting from the Toyota production system, Lean Manufacturing has been widely adopted by various sectors such as automotive, electronics, health and pharmaceuticals to optimize resource use and improve product quality (Saboo et al., 2014; Ghosh, 2012; Nordin et al., 2014). The basic principles of Lean Manufacturing emphasize continuous improvement and elimination of

non-value added activities, which are essential to achieve operational efficiency (Pratama et al., 2019). Research shows that organizations that implement Lean practices can significantly improve operational performance, which is evident in numerous case studies showcasing improved metrics in manufacturing environments (Ghosh, 2012; Nordin et al., 2014).

The integration of advanced digital technologies, such as Artificial Intelligence (AI) and the Internet of Things (IoT), has increasingly transformed the manufacturing landscape. AI enables manufacturing systems to analyze data, predict outcomes, and automate decision-making processes, thereby increasing operational efficiency (Barari et al., 2021; Petrillo et al., 2022). On the other hand, IoT facilitates real-time data exchange between devices, creating a responsive production environment that is aligned with Lean principles, by minimizing waste and optimizing resource allocation (Petrillo et al., 2022; Palanisamy, 2023). This technological convergence not only streamlines production monitoring and predictive maintenance, but also supports the primary goals of Lean Manufacturing through the development of a culture of continuous improvement and adaptability (Khan et al., 2023; Petrillo et al., 2022).

In production environments with high variability, where demand fluctuations and design changes occur frequently, Lean Manufacturing faces its own challenges. The dynamic nature of this industry requires a flexible approach to maintain consistent quality and efficiency (Ghosh, 2012; Nordin et al., 2014). The application of AI and IoT technology offers solutions for developing adaptive Lean Manufacturing systems that are able to adapt to changing production conditions in real-time (Khan et al., 2023; Palanisamy, 2023). This adaptability is critical for organizations that want to remain competitive in a rapidly changing market, as it allows for seamless integration of Lean with advanced technology solutions (Petrillo et al., 2022; Palanisamy, 2023).

In conclusion, Lean Manufacturing remains a fundamental strategy for improving operational efficiency in various industries. The integration of AI and IoT technologies not only complements Lean principles but also addresses the challenges faced in high-variability production environments. As the industry develops, the synergy between Lean Manufacturing and advanced digital technology will become a crucial factor in driving competitiveness and innovation.

This research is motivated by the existence of problems and gaps in the literature related to the integration of advanced digital technology within the Lean Manufacturing framework. Although the application of Lean Manufacturing has been widely discussed in the literature, the integration of advanced technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) in this context is still relatively new and underexplored. Most current research only focuses on individual applications of AI or IoT in production processes, while the impact of their combination within a Lean Manufacturing framework has not been widely studied. Additionally, there is a gap in understanding how technologies such as AI and IoT can support key components of Lean, such as Just-in-Time (JIT) and Kanban, especially in environments that demand rapid response to production variability.

Companies operating in production environments with high levels of variability often face major challenges in maintaining efficiency and reducing waste. Fluctuating demand or frequent changes in product specifications can result in longer lead times, unnecessary increases in inventory, and other types of waste. Technologies such as AI that can predict demand and IoT that can monitor production conditions in real-time have great potential to help overcome this problem. However, the literature examining the specific benefits of integrating these technologies in high-variability environments is limited. Thus, there is an opportunity to research more deeply into how to apply this digital technology within the Lean Manufacturing framework.

This research aims to understand how the integration of AI and IoT within a Lean Manufacturing framework can increase operational efficiency and reduce waste, especially in

production environments with high levels of variability. This study is expected to contribute to the literature by identifying effective methods for combining advanced digital technologies with Lean principles, so that companies can more easily adapt to rapid changes in the market.

The main questions that will be answered in this research are: “How does the integration of advanced digital tools (such as AI and IoT) within a Lean Manufacturing framework impact operational efficiency and waste reduction in a high-variability production environment?” This question is aimed at deepening understanding of the contribution of AI and IoT in reducing waste and speeding up responses in the context of Lean Manufacturing, the resulting flexibility in the production process, as well as the challenges that companies may face in implementing digital technology in Lean systems in high variability environments.

Based on this background, the research will conduct a systematic review of existing literature to answer these questions, identifying general patterns, challenges and opportunities in integrating AI and IoT with the Lean Manufacturing framework in the context of high production variability.

2. Methods

2.1. PRISMA Approach

To ensure that the process of searching, selecting and evaluating literature is carried out systematically and transparently, this research uses an approach Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISM). PRISMA is a standard guideline in literature reviews that focuses on transparency and traceability, enabling researchers to identify, select, and analyze relevant articles systematically. By using PRISMA, this research adopts a structured framework in reporting study results, which ensures that all decisions in the literature selection process can be accounted for.

2.2. Data Sources and Search Strategy

- Data source
  This study relied on several major academic databases to search for articles relevant to the topic, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect. These databases were selected for their broad coverage in the areas of manufacturing, digital technology, and operations management, and include many indexed publications in high-quality journals.
- Search Strategy
  The search strategy used involved keywords combined with Boolean operators to identify specifically relevant studies. The main keywords used in the search were "Lean Manufacturing," "AI," "IoT," "operational efficiency," "waste reduction," and "high-variability production." The use of these keywords is designed to cover studies that explore the integration of digital technologies within the framework Lean Manufacturing, especially as it relates to improving operational efficiency and reducing waste in high-variability production environments.
- Inclusion and Exclusion Criteria
  To ensure the relevance and quality of the analyzed articles, the following inclusion and exclusion criteria were applied:
    - Inclusion Criteria: The selected article is an article peer-reviewed written in English, published within the last five years to ensure relevance to the latest technological developments, and has a focus on the impact of AI and IoT in the context of Lean Manufacturing. Selected articles should present empirical evidence or in-depth analysis related to operational efficiency or waste reduction in a manufacturing environment.
    - Exclusion Criteria: Articles that are not relevant to the context Lean Manufacturing or those that only discuss technology (AI or IoT) without a specific link to the principles Lean and operational efficiency in a production

environment will be excluded. Articles with a limited focus on one aspect without explicit linkage to the overall framework Lean Manufacturing also excluded.

2.3. Screening and Study Selection

- Initial Screening Process
  The selection process begins with screening the beginning of the search results in the database. At this stage, the titles and abstracts of all articles resulting from the search will be checked to ensure relevance to the research topic. Articles that clearly did not meet the inclusion criteria or that met the exclusion criteria were removed from the analysis.
- Abstract Screening dan Full-Text Screening
  After screening initially, articles that meet the criteria will enter the stage abstract screening And full-text screening. At this stage, the article abstracts will be further analyzed to ensure that they truly cover the topic of deep digital technology integration Lean Manufacturing and that they present empirical evidence or analysis appropriate to the research focus. Articles that pass this stage will then be checked in full (full-text) to evaluate their suitability to the research objectives and inclusion criteria.
- Screening Tool
  To ensure consistency and transparency in the process screening, tools like Rayyan or coexistence are used. These tools facilitate the process of screening articles collaboratively, allowing researchers to manage references, flag relevant articles, and track decisions of inclusion/exclusion for each article. Use of this tool also helps ensure that each article selected for analysis meets rigorous standards and is relevant to the research objectives.

2.4. Data Extraction and Analysis

- **Metode Data Extraction**
  After the selection process is complete, the next stage is data extraction from articles that have passed the selection. The data to be collected includes important information such as:
  - Research variables: variables measured in the study, such as operational efficiency, waste reduction rates, or specific impacts of AI and IoT.
  - Methods used: research methods used in each article, whether qualitative, quantitative, or a combination of both.
  - Main results: the main findings of each study regarding the impact of integrating digital technologies in the framework Lean Manufacturing.
  - Aspects focused on production variability: how the study identifies and measures variability in production and approaches to managing that variability with AI and IoT. This data extraction was carried out systematically to ensure that all articles analyzed had uniform and relevant data to be interpreted in the research context.
- **Analysis Method**

After the data is collected, the analysis method used is qualitative synthesis to identify general patterns, trends, and gaps in the literature. Qualitative synthesis will help understand how technologies such as AI and IoT have been applied in various frameworks Lean Manufacturing, as well as how they contribute to efficiency and waste reduction in various types of industries, especially those with high levels of production variability. This analysis will also evaluate factors that influence the success or challenges of integrating digital technologies within the framework Lean. The results of this analysis will be used to identify further research opportunities and provide recommendations for future studies.

With this structured method, the research is expected to provide a comprehensive and high-value contribution to the literature related to the integration of AI and IoT within the framework Lean Manufacturing, especially in production contexts with high variability.

3. Results

3.1. Description of the Study Obtained

3.1.1. General Profile of Selected Articles

This study collected and analyzed relevant articles discussing implementation of Lean Manufacturing with the support of advanced digital technologies, especially AI and IoT, in a manufacturing environment characterized by high variability. Of the total articles selected, a number of articles specifically discuss the application of AI and IoT in the Lean Manufacturing process. These studies come from various industries that have varying production characteristics, such as automotive, electronics, and the food and beverage industry. The number of articles that directly address the integration of AI and IoT in Lean processes, as well as the focus on highly variable production, is an indicator of the growing interest in the academic literature on this topic.

3.1.2. Distribution of Years and Types of Research

The articles selected were mostly published within the last 10 years, indicating this topic is a still developing research area. The types of research found include data-based quantitative studies, industrial case studies, and literature reviews related to the implementation of digital technology in the context of Lean Manufacturing. Most articles use experimental methods or case studies in real industries, indicating that many findings are practical and based on direct testing in the field.

3.2. Key Findings

3.2.1. The Impact of Technology Integration on Operational Efficiency

- **The Role of AI in Increasing Efficiency**
  The analyzed articles show that AI has an important role in improving operational efficiency through diverse applications, such as predictive maintenance And quality control. In predictive maintenance, AI is used to analyze sensor data on machines and predict potential failures before they occur, which can reduce machine downtime and increase operational availability. Meanwhile, quality control AI-based technology is able to automatically identify product defects in production lines, allowing immediate corrective action to be taken, thereby reducing the production of defective goods and increasing acceptable production output.
- **Role of IoT in Real-Time Tracking and Quick Decision Making**
  Studies show that the use of IoT in variable production environments allows companies to monitor operations continuously real-time through a network of sensors placed along the production line. IoT sensors provide detailed data on machine status, raw material condition and work flow, allowing operators to dynamically adjust processes. For example, by using IoT to monitor energy or raw material usage, companies can identify areas of potential waste and make quick improvements to keep Lean Manufacturing efficiency in optimal condition.

3.2.2. Impact on Waste Reduction

- **Use of IoT Technology in Reducing Material Waste**
  IoT integration makes a significant contribution to reducing material waste through optimizing the use of raw materials and monitoring production processes continuously. Sensors connected via IoT can

provide warnings when raw material usage exceeds permitted limits or when energy is wasted. For example, companies can use IoT data to monitor the ratio of raw materials used in production and minimize wasted material. As a result, production becomes leaner and material costs can be reduced significantly.

- **Operational Error Detection and Prevention**
  Studies also show that the use of AI in error detection helps identify and correct problems before they have a significant impact on production output. For example, AI integrated in a Lean Manufacturing system can learn error patterns from historical data and automatically identify the root causes of possible errors. With this early detection, companies are able to reduce waste caused by repeated production errors, which ultimately supports Lean goals in creating lean and efficient processes.

3.2.3. Identify Challenges and Limitations

- **Obstacles in Implementing Digital Technology in Lean Manufacturing**
  - **Implementation Costs and Investment Sustainability**
    One of the biggest challenges identified in the literature is the high cost of implementing AI and IoT technologies in Lean Manufacturing systems, especially in small and medium-sized companies. Many studies reveal that the costs of procuring hardware and software, system integration, and training the workforce to use this technology require significant initial investment. Therefore, investment sustainability is a challenge for companies that have limited budgets but want to remain competitive in the market.
  - **Skill Limitations and Resistance to Change**
    The articles also highlight limited workforce skills as a major barrier to the adoption of advanced technologies in Lean Manufacturing. Employees accustomed to conventional processes often show resistance to new technological changes and require additional training to be able to use AI and IoT tools effectively. This challenge is especially felt in industries that have a workforce with low digital skills, where the integration of digital technology requires quite fundamental changes in work culture.
- **Analysis of Other Factors Affecting Technology Integration**
  In addition to cost and skills, other factors identified in the literature include technological complexity, data security risks, and the need for reliable digital infrastructure. Several studies show that the integration of AI and IoT increases data security risks due to the use of interconnected networks. Therefore, companies need to consider security aspects in every technology implementation to maintain data integrity and confidentiality.

3.2.4. Identify Research Gaps

- **Gaps in Understanding the Long-Term Effects of Technology Integration in Lean Manufacturing**
  One of the main research gaps identified was the lack of studies exploring the long-term impacts of using digital technologies such as AI and deep IoT Lean Manufacturing. Most studies only cover short-term effects or initial implementation without measuring ongoing impacts, especially in production environments with high variability. Long-term research is needed to

understand how this technology impacts efficiency and waste reduction over longer periods of time.

- **Limitations of the Study in the Context of High Variability in Production**
  Many articles in the current literature still focus on implementing Lean Manufacturing in production environments with low or medium variability, while research targeting production with high variability is still limited. High variability creates unique challenges that require a specialized approach to digital technology integration. Further research is needed to dig deeper into how AI and IoT can adapt in conditions of high variability and still maintain Lean principles in operational management.

4. Discussion

4.1. Implications of Findings

4.1.1. Increased Understanding of AI and IoT Integration in Lean Manufacturing

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) into the Lean Manufacturing framework has been proven to be able to increase operational efficiency and reduce waste significantly. This integration is in line with Lean Manufacturing principles which emphasize waste reduction and continuous improvement. Results from various studies show that AI can support predictive maintenance, thereby reducing downtime and optimizing machine performance. For example, AI analysis capabilities combined with real-time data collection from IoT enable better decision-making processes and resource allocation in manufacturing environments (Dmitrieva, 2024).

IoT technology has an important role in monitoring production processes in real-time, which increases transparency in the use of raw materials and enables early detection of potential waste. Research shows that IoT-based systems are able to manage waste effectively by providing deep insight into operational inefficiencies (Bakhar, 2023; Rao, 2024). For example, the application of IoT in manufacturing processes has been proven to be able to reduce waste production significantly, as revealed in studies regarding the effectiveness of IoT in waste management systems (Wang, 2024; Ali, 2023). In addition to supporting waste reduction, the integration of this technology also builds a culture of sustainability in manufacturing operations (Baldini et al., 2023).

Furthermore, the integration of AI and IoT in Lean Manufacturing results in measurable efficiency improvements and improves overall production quality. The use of IoT devices enables continuous monitoring and feedback, which is essential for maintaining high standards in manufacturing processes (Wofuru-Nyenke, 2021; Ghobadian et al., 2020). The synergy between AI and IoT technologies creates a powerful framework to address current operational challenges as well as prepare organizations for future developments in manufacturing practices (Rao, 2024; Santhosh et al., 2020). This holistic approach of integrating advanced technologies with Lean Manufacturing principles reinforces that AI and IoT can significantly support and enhance the core goals of the Lean methodology.

In conclusion, the integration of AI and IoT within a Lean Manufacturing framework offers transformative opportunities for organizations to increase operational efficiency and reduce waste. Evidence from various studies supports the statement that this technology can create a more effective waste monitoring and management system, which is in line with the main goals of Lean Manufacturing.

4.1.2. Practical Implications for Companies with High Variability

The results of this research have direct implications for companies with high variability in production, such as the automotive and electronics sectors, where demand and product specifications can change dynamically. The integration of Internet of Things (IoT) technology into manufacturing processes significantly increases responsive monitoring capabilities, enabling companies to adapt to rapid changes in design and customer demands. By leveraging

real-time data on material flow and production status, organizations can maintain Lean principles while increasing flexibility. This adaptability is critical in an environment that requires production variations to meet diverse customer needs. IoT technology facilitates a seamless flow of information, enabling manufacturers to make data-driven decisions that adhere to Lean methodology, thereby optimizing efficiency without sacrificing responsiveness.

Research shows that the Industrial Internet of Things (IIoT) plays a critical role in creating manufacturing intelligence through real-time data transmission across industrial networks. The integration of IoT with other technologies such as big data and machine learning makes it possible to carry out intelligent operations that are essential for maintaining Lean principles in a dynamic market (Saqlain et al., 2019; Ghelani, 2021). Furthermore, the combination of IoT and Lean practices is proven to improve operational performance, where both approaches complement each other in increasing efficiency and reducing waste (Buer et al., 2020; Rosin et al., 2019). The real-time capabilities of IoT technology enable manufacturers to visualize and manage production processes more effectively, leading to faster response times and better alignment with customer demands (Trubetskaya et al., 2023; Çakır et al., 2022) .

Additionally, the application of IoT in manufacturing not only supports Lean principles but also drives innovation and transformation in the industry. For example, the integration of IoT with Lean practices has been identified as a way to revolutionize traditional manufacturing processes, making them more agile and responsive to market changes (Florescu & Barabas, 2022; Valamede & Akkari, 2020). This synergy allows companies to implement advanced monitoring systems that provide timely insights into production inefficiencies and potential risks, ultimately improving process efficiency (Argiyantari et al., 2020; Zhang et al., 2018). The ability to adapt quickly to change while remaining compliant with Lean methodology puts companies in a strong position to compete in an increasingly competitive marketplace.

Overall, leveraging IoT for responsive monitoring in manufacturing environments increases a company's ability to adapt processes and reduces response times to changes. By integrating IoT technology with Lean principles, organizations can achieve greater flexibility and efficiency, ensuring their competitiveness in a rapidly evolving marketplace.

4.1.3. Strengthening Lean Manufacturing with Digital Technology in Reducing Waste

The integration of digital technologies, particularly the Internet of Things (IoT) and Artificial Intelligence (AI), into Lean Manufacturing practices has proven promising in improving waste reduction efforts. Lean Manufacturing, which has traditionally focused on waste minimization and process optimization, can benefit from the real-time data and analytical capabilities provided by these digital technologies. For example, IoT devices can continuously monitor energy consumption and raw material use, allowing companies to detect inefficiencies and waste before they become larger problems (Bakhar, 2023). This proactive approach is in line with the main principles of Lean Manufacturing, namely continuous improvement and elimination of waste.

Additionally, the combination of Lean Manufacturing with Industry 4.0 technologies, including AI and IoT, creates a more adaptive manufacturing environment. Research shows that the integration of these technologies not only supports traditional Lean practices but also increases operational flexibility and responsiveness to market changes (Saad et al., 2021; Narula et al., 2022). For example, AI can analyze production data to predict demand and optimize inventory levels, thereby reducing excess waste (Ayoubi, 2023). This synergy between Lean principles and digital technology results in more efficient production processes, especially in environments characterized by high variability (Narula et al., 2022).

Furthermore, studies show that digital supply chain practices significantly contribute to the effectiveness of Lean Manufacturing. The use of digital technologies in the supply chain enables better resource allocation and improves the overall performance of the manufacturing process (Rahamneh et al., 2023; Núñez-Merino et al., 2020). By leveraging data analytics and

IoT, companies can streamline their supply chains, reduce lead times, and increase customer satisfaction—all important components of Lean Manufacturing (Ooi et al., 2023). This integration not only supports waste reduction, but also encourages a culture of continuous improvement that is essential to maintaining competitiveness in today's dynamic marketplace (Solheim & Powell, 2020).

Overall, the integration of digital technologies such as IoT and AI into the Lean Manufacturing framework offers a powerful strategy for waste reduction. By enabling real-time monitoring and data-based decision making, this technology increases the adaptability and efficiency of manufacturing processes, thereby strengthening Lean Manufacturing principles. As companies continue to adopt these advancements, the potential to achieve sustainable operational excellence becomes increasingly attainable.

4.2. Study Limitations

4.2.1. Limited Number of Studies in High Variability Contexts

One of the limitations identified in Systematic Literature Review This is a limited number of studies that specifically look at the application of Lean Manufacturing with digital technology in companies that have a high level of production variability. Most of the available literature focuses on production environments with low or stable variability, such as in the mass manufacturing sector. These limitations create gaps in the literature that hinder a deeper understanding of the effectiveness of digital technology implementation in facing the challenges of high variability in certain industries.

4.2.2. Variations in Definitions of Operational Efficiency and Waste Reduction

The studies analyzed in the literature also show variations in the definition and measurement of operational efficiency and waste reduction. Some studies use efficiency indicators such as cycle time and machine downtime, while others use cost and resource usage-based indicators. This inconsistency in measurements is an obstacle in the process of comparing results between studies and in identifying consistent patterns regarding the impact of AI and IoT technologies on Lean Manufacturing. This limitation is also a factor that influences the generalization of the results of this research to a wider context.

4.3. Future Research Directions

4.3.1. Advanced Exploration of High Variability in Production

Based on existing findings, it is recommended that future research focus more on how high variability in production influences the successful implementation of Lean Manufacturing together with digital technology. Production conditions with high variability require greater flexibility in operations and more responsive waste monitoring, which is not fully covered in the current literature. Deeper exploration could include studies that focus on the relationship between the degree of variability and the effectiveness of digital technology in supporting Lean principles, as well as how this variation impacts operational efficiency in various production scenarios.

4.3.2. Case Studies in Specific Industrial Sectors with High Variability

The next recommendation is to conduct case studies in industrial sectors that have high variability, such as the automotive, electronics or consumer product manufacturing sectors. Case studies in these sectors will provide a more contextual understanding of how AI and IoT function in dynamic production environments. By conducting more in-depth studies in specific industries, researchers can identify technology adoption patterns unique to that sector as well as specific challenges that may not be found in industries with low variability. This kind of research can provide more relevant and applicable empirical data for companies wishing to adopt digital technology in a complex and changing Lean Manufacturing environment.

4.3.3. Development of an Efficiency and Waste Evaluation Framework with Digital Technology

As part of future research directions, it is recommended to develop a more consistent evaluation framework in measuring operational efficiency and waste reduction under the influence of digital technologies. This framework may include specific metrics for predictive maintenance, AI-based quality control, as well as IoT-based waste indicators. By developing a uniform evaluation matrix, companies can more easily compare the results of digital technology implementation across different sectors and production environments, giving them a clearer understanding of the added value of integrating AI and IoT into the Lean Manufacturing framework.

5. Conclusion

5.1. Summary of Key Findings

This research highlights the significant role of digital technologies, especially AI and IoT, in enriching the application of Lean Manufacturing, especially in production environments with high variability. AI integration, through applications such as predictive maintenance and data-based quality control, is proven to reduce downtime, improve product quality and optimize operational efficiency. IoT, through tracking and monitoring systems real-time, enables full transparency across the entire production process, enabling companies to more quickly identify and reduce material and energy waste. Thus, this research provides evidence that the combination of AI and IoT can improve Lean Manufacturing's ability to maintain efficiency while minimizing waste in fluctuating production conditions. This is answered by a research question proposed, namely how the integration of AI and IoT in Lean Manufacturing can contribute to increasing efficiency and reducing waste.

5.2. Managerial Implications

The findings of this research carry practical implications for operational managers and industrial leaders, especially those operating in manufacturing environments with high levels of variability. For managers, the adoption of technologies such as AI and IoT is not just an additional tool but a strategic necessity to maintain efficiency and effectiveness within a Lean Manufacturing framework. AI can help managers make data-based decisions, for example in predicting when machines need maintenance or identifying potential errors before they occur. Meanwhile, IoT enables comprehensive process monitoring, which is useful for detecting waste and making timely improvements. By adopting this digital technology, companies can gain competitive advantages through increased efficiency, quality and responsiveness to changes in market demand.

Implementing digital technologies within the Lean framework also present challenges that industry leaders need to be aware of, such as the need to train employees with new skills in the use and analysis of AI and IoT-generated data. Therefore, managers need to consider investing in internal training programs, as well as developing long-term strategies for continuous technology adaptation. This becomes important in the era of industrial digitalization, where speed and flexibility in production processes are the keys to competing in the global market.

This research makes an important contribution to the literature, by filling the existing gap regarding the integration of digital technologies within the Lean Manufacturing framework, especially in the context of production environments with high variability. This study confirms that AI and IoT are not just technological innovations, but also transformational tools that can strengthen the implementation of Lean Manufacturing in achieving optimal efficiency and reducing waste significantly. For industry, this research shows that the application of digital technology in Lean Manufacturing is an important step for adaptation in the industrial era 4.0, where digitalization and automation continue to redefine operational standards and efficiency.

With this research, it is hoped that manufacturing companies, especially those operating in an environment full of variation and change, can see the opportunities and potential of integrating digital technology as part of their Lean strategy. This research also opens up opportunities for further, more in-depth studies regarding the practical challenges and long-term results of digital technology integration in Lean Manufacturing. Overall, this research contributes to the development of relevant and applicable insights for academics, practitioners and industry leaders in the digital era.

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