The Synergy of Lean Principles and Artificial Intelligence: Towards Smart and Sustainable Operations

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Abstract. Under the background of moving towards Industry 4.0 and Industry 5.0, the digital transformation of companies, especially manufacturing enterprises, is very important for reducing costs, increasing efficiency, and enhancing profitability. This study aims to explore the profound integration and strategic synergy between artificial intelligence technology and lean management principles. Traditional lean practices largely rely on human experiential judgment and visual process analysis, while AI technology, with its powerful data-driven insights, pattern recognition, and predictive analytics, provides unprecedented accuracy, breadth, and foresight in the implementation of lean principles. This paper clarifies the ultimate goal of management combined with AI technology—organisational evolution through continuous improvement and learning—based on the fourteen principles of lean management, using bibliometric methods and case analyses. The study aims to illustrate the intelligent lean systems of human-machine collaboration and the strategic, organizational, and cultural aspects that need to be considered, ensuring smoother transitions and better adoption of new technologies.

Keywords: Lean, Artificial Intelligence, Industry 5.0

1 Introduction

We are in the midst of a wave of change in the era of Industry revolution. These processes must be supported by appropriate infrastructure, such as the Internet of Things (IoT), as well as other suitable hardware and software means to achieve full vertical and horizontal integration of all enterprise functions from the executive level to the shop floor. The manufacturing industry is increasingly adopting advanced technologies to improve efficiency and automation of its manufacturing processes. Artificial intelligence (AI) has emerged as a disruptive technology, increasingly being applied to different professional and scientific domains. They provide predictive insights, efficient manufacturing operations planning, real-time optimization [1]. By leveraging these innovations, companies can reduce downtime and reduce inefficiencies throughout the supply chain, ensuring smoother and reliable operations. While digitalization and automation have significantly improved industrial automation, human creativity and problem-solving abilities remain essential [2].

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Lean, associated with Toyota and the Toyota Production System, is often used in engineering industry. Since the publication of "The Machine That Changed the World" [3], lean manufacturing (LM) has been recognized as a world-recognized management philosophy. It became an advanced manufacturing strategy enhancing productivity, maximizes quality, and eliminates waste. The lean production system aimed at improving processes by aligning employees with a common vision. Implementing lean principles suitable for the organization will achieve higher performance, thereby increasing the competitiveness of the enterprise. Within the lean production system, various principles stand out, including standardization, zero defects, pull and flow production, and employee orientation, which are among the 14 lean principles. Sustainability is considered as the new frontier of lean manufacturing. Productivity and cost savings are essential for the economic survival of an organization should be achieved by reducing negative environmental and social impacts and contributing to a sustainable society [4]. Industry 4.0 is reshaping the competitive landscape and value creation mode of the global manufacturing industry. Industry 5.0 is also a new manufacturing revolution. It is essential to consider performance from a multidimensional perspective, considering environmental and social impacts. There is increasing pressure from stakeholders across the entire value chain, demanding that this ongoing pursuit of efficiency and competitiveness should not come at the expense of the environment or the social conditions of citizens.

The literature research on the integration of artificial intelligence (AI) and lean management is currently in a thriving stage. A large number of studies focus on how AI technology empowers various core principles and tools of lean management, such as using machine learning algorithms for more accurate demand forecasting and anomaly detection to support Just-In-Time (JIT) production and Jidoka, achieving dynamic self-optimization of processes, and advancing lean management to "smart lean." However, there are still several significant issues in this field of study. Firstly, theoretical research outweighs practical applications, with most results staying at the level of framework construction and potential description, lacking large-scale and long-term successful empirical cases in complex real industrial scenarios. Secondly, there is insufficient attention to the cultural and social dimensions; existing literature often overlooks the human factors in the AI-empowered environment, such as employee engagement, organizational cultural change, and new modes of human-machine collaboration. Therefore, in this study, we use bibliometric methods and case studies to focus more on the strategic, organizational, and cultural aspects required to achieve the organic integration of AI and lean management, and to address the aforementioned bottleneck issues through rigorous empirical research.

2 Research Methods

2.1 Bibliometric Analysis

This article studies journal literature, primarily integrating information and data mining from the perspectives of highlighted words, keywords, cluster words, and timelines. It summarizes the developmental characteristics of lean management research combined

with AI technology, gaining insights into the dynamics and focal issues in the field, which is of significant reference value for researchers conducting related theoretical studies.

Web of Science (WOS) was selected as the literature resource for this study. By searching for keywords such as 'lean production', 'artificial intelligence', 'Industry 4.0', and 'management', and restricting the time frame to 2021-2025, a total of 2038 relevant English articles were retrieved from the WOS core database. After filtering, 1028 articles are remained belong to the fields of engineering, computer science, materials science. Using the Citespace software of the 6.2.R1 version to conduct a visual analysis of internationally influential academic journals, employing text information extraction methods and a combination of qualitative and quantitative approaches, we can uncover the current research hotspots in this field globally, as well as reveal its evolutionary trajectory and development trends.

2.2 Case Study

Case study is a commonly used qualitative research method that is suitable for conducting in-depth and comprehensive investigations of a specific problem in reality. Through case studies, we can describe and explore the current state and development of a particular issue. Case studies may also drive people to establish new theories or revise existing ones.

The case study method, as an important qualitative research approach, aims to reveal the inherent laws and mechanisms behind complex phenomena by conducting an in-depth and systematic examination of the use of AI in lean management work environments. This method discovers new theoretical perspectives or constructs theoretical frameworks in specific practical contexts. Its significance lies in providing deep insights into research questions through contextualized analysis. Thus enhancing the practical relevance and theoretical contribution of the research, and providing a solid empirical foundation and theoretical insights for future studies.

3 Results and Findings

3.1 Keywords Hotpots

The analysis settings are: LRF=2.5; L/N=10; LBY=5; e=1.0. Pathfinder has pruned the slice network and co-occurrence network graphs.

As shown in Figure 1, the three initial search keywords—artificial intelligence, management, and Industry 5.0, have the highest frequency and the largest nodes. After removing these keywords, the top ten keywords sorted by frequency are digital twin, optimization and improvement, big data, machine learning, smart manufacturing, digital transformation, augmented reality, sustainable development, human-machine collaboration, and circular economy. Among them, the most prominent keywords ranked by centrality are automation, human-machine collaboration, and smart manufacturing.

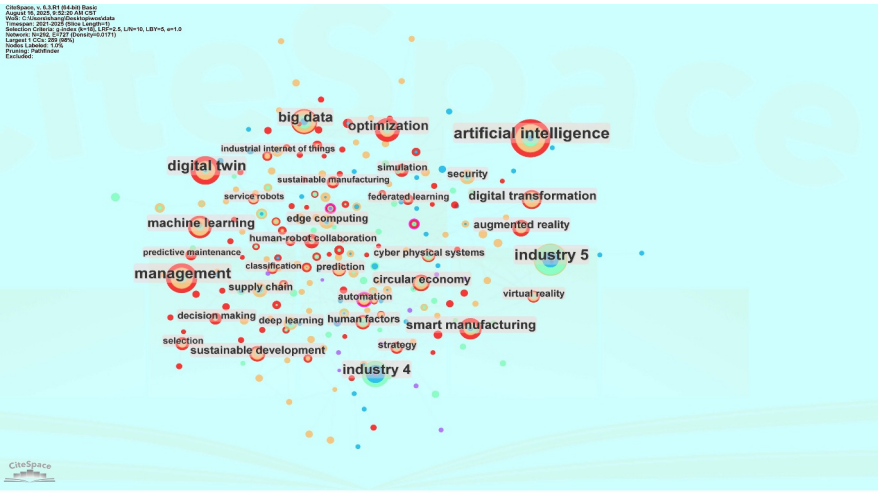

Fig. 1. Keyword co-occurrence map.

Top 25 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2021 - 2025
industry 5	2021	24.81	2021	2023	
industry 4	2021	19.02	2021	2023	
society 5	2021	4.43	2021	2022	
internet	2021	3.55	2021	2022	
innovation	2021	2.87	2021	2023	
big data	2021	2.52	2021	2022	
implementation	2021	2.17	2021	2022	
energy	2021	1.96	2021	2022	
edge computing	2021	1	2021	2022	
architecture	2022	3.14	2022	2023	
smart city	2022	2.64	2022	2023	
network	2022	2.31	2022	2023	
cyber physical systems	2022	1.44	2022	2023	
resource allocation	2022	0.89	2022	2023	
intelligence	2022	0.78	2022	2023	
human robot collaboration	2022	0.52	2022	2023	
internet of things (iot)	2023	1.73	2023	2025	
chatgpt	2023	1.3	2023	2025	
parallel intelligence	2023	1.15	2023	2025	
quality	2023	1.15	2023	2025	
edge	2023	1.15	2023	2025	
supply chain management	2023	1.01	2023	2025	
cyber-physical-social systems	2023	0.87	2023	2025	
anomaly detection	2023	0.87	2023	2025	
social sustainability	2023	0.87	2023	2025	

Fig. 2. Top 25 keywords with strong citation bursts.

Keywords with strong citation bursts can capture the changes in high-frequency keywords, focusing on cutting-edge content, identifying academic hotspots and development trends. As shown in Figure 2, this table includes 25 explosive keywords that present a yearly evolution trend from 2021 to 2025 in chronological order.

Stepping forward to the Industry 4.0 and Industry 5.0, the research focus from 2021 to 2023 covers big data, edge computing, resource allocation, and human-machine collaboration. In the past three years, parallel intelligence in the Internet of Things, supply chains, and social sustainability have become research hotspots between the combination of AI and lean management.

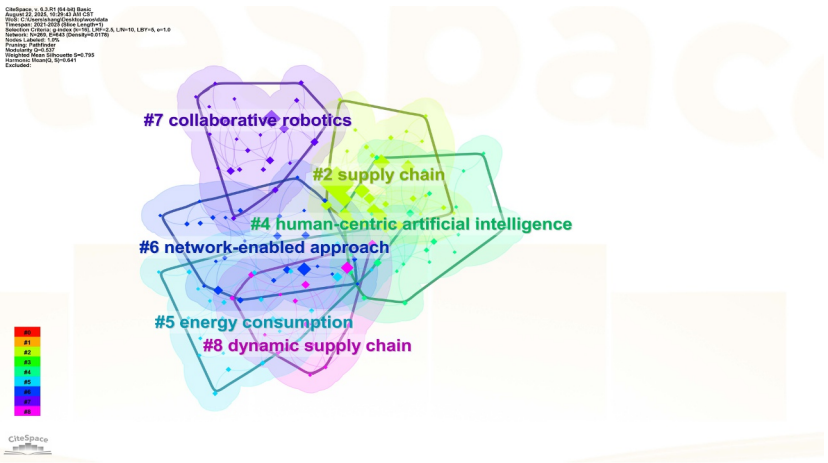

Fig. 3. keyword co-occurrence network clustering.

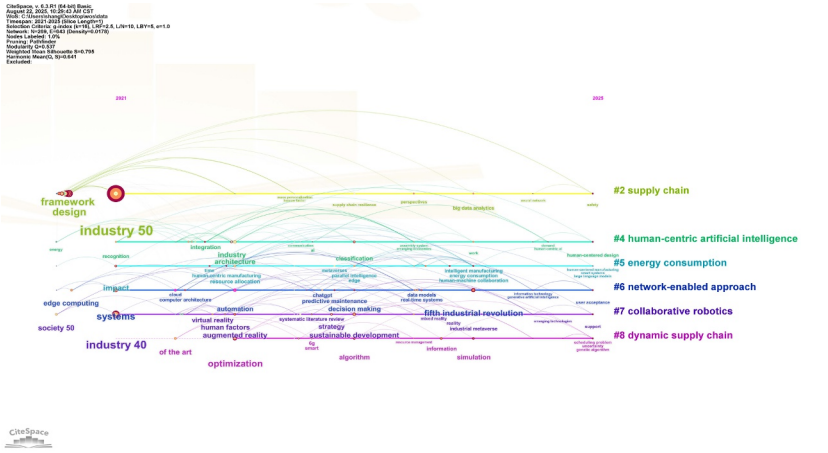

Fig. 4. Keyword co-occurrence network timeline.

Combining the two images, Figure 3 and Figure 4, it can be observed that part of the research focus on AI and lean management is on the supply chain and the application scenarios of digital and intelligent transformation of enterprises; the other part emphasizes human subjectivity more strongly. Based on the characteristics of AI, such as its autonomy, adaptability, intelligent interaction, and big data processing capabilities, it can help business managers predict market demand and make optimal decisions during the digital transformation process. Furthermore, the latest timeline indicates that human-machine collaboration will be a key focus of future research. After the integration of AI into lean manufacturing workplaces, employee acceptance, work engagement, and better supporting employees in their roles will become directions for future development. This aligns with the core principle of lean, which is to respect people.

3.2 Case Research

Case 1: AI is more commonly applied in our workplace. It not only brings huge improvements in efficiency and new possibilities, but also triggers profound ethical concerns and employee resistance. It may reduce employee engagement. The concept of employee engagement, defined as "the union of organizational members with their work roles; people use and express their physical, cognitive, and emotional selves in the process of role-playing". Traditional EE seeks to establish a sense of belonging to the organization through high levels of commitment. In lean management, employees can be empowered to provide and implement improvement suggestions to change work environment. EE requires excellent performance results while improving job satisfaction and quality of work [5].

In order to find out whether it pose negative impacts on EE, a study was conducted in an automotive company, which introduce machine learning for quality inspection, result in a 23% reduction in scrap and quality rework levels by recommending process adjustments to upstream workstations through an assembly line business intelligence panel. When asked about the impact of AI on assembly line employee engagement, the employee believes that AI integration helps complete activities that require less creativity, allowing him to focus on truly value-added activities. It also helps team members design solutions faster and more decisively. Another beverage manufacturer with multiple plants in Australia, with the help of artificial intelligence, the machine reminds operators when and where to fix any problems with the machine, suggests appropriate corrective actions, and records and learns from it to improve its system. Since its inception, the overall equipment efficiency in the region has increased from 67% to 79%, with an increase of approximately 18% between failures [6]. Operators and team leaders are positive about the impact of AI on employee engagement, believing that this technology prevents wasteful activities and saves time and effort. This contributes to team building and a more collaborative environment, regardless of the skill level of employees. It also increases pride in what you do and confidence in your team, creating a safer work environment.

From an employee's insight, the use of AI proves reliable, can promote collaboration in the workplace, and prevent employees from performing basic and repetitive activities. This leads to more positive personal interrelationships and group dynamics, improving emotional engagement among employees [7]. In addition, they can use AI to improve communication and knowledge sharing so that it is beneficial to become a learning organization through relentless improvement. From a manager's insight, adopting AI enables him to understand the whole situation in a broader insight. He will find exceptional people more easily and team members mostly following company's culture and mostly involved.

Therefore, AI in the work environment do good on employees' physical engagement, contributing to increased meaningfulness and usability of work. Experts believe that in lean organizations, the use of AI tends to reduce the physical and mental effort that employees put in to complete activities. With less physical and mental effort, employees can devote their energy to more value-added activities that truly challenge their creativity and fully realize their potential.

From a cognitive perspective, AI adoption is beneficial to increased communication and knowledge sharing. Researchers have found that suggestions or answers generated by artificial intelligence are perceived to be more empathetic than human responses. With the support of AI, people can enhance their emotional understanding and awareness. This can improve the trust experience and closeness in interpersonal interactions, allowing individuals to experience more civil and respectful communication in the workplace [8]. The specific determination and guidance of operational tasks by AI seems to clarify expectations for employees' roles, reduce their anxiety and increase their self-confidence.

Case 2: TC, located in Taiwan, is a leading technology services provider that specialize in the design, produce, services and systems of mobile communication related products. The organizational culture emphasizes innovation and incorporates sustainability and innovation-related elements into its overall vision and mission. In the process of providing customized products to customers, it was found that the large number of requirements generated often resulted in a large number of defects. To address this problem, the project first formed a dedicated team and designated a leader, who explored potential solutions to reduce the number of defects using lean tools combined with technical support such as artificial intelligence. The company used artificial intelligence models to optimize the operation of its large physical system, thereby improving efficiency. The training of the optimization model takes only 20 minutes, saving tens of millions of dollars in energy consumption each year. Artificial intelligence enables factory managers to determine the most suitable equipment for each task in real time, thereby optimizing the movement of batches within factories and warehouses. AI applications in factories control robot arms and individual machines, allowing them to operate in coordination without excessive or repeated use. Error-proofing technology also involves artificial intelligence technology. For example, this feature enables the robot to identify touch panels with smooth surfaces so that they can be placed in the cutting machine. The situation before and after the implementation of zero-defect manufacturing with advanced technology, the whole project directly saved NT$104,000, mainly due to higher production yields and reduced rework processes. The case company explores the combination of AI and lean tools to improve processes based on the management goals of innovation and sustainability, avoiding overproduction and imbalances in production pressure. At the same time, artificial intelligence helps with quality assurance, visualizing issues for timely rectification, ultimately achieving standardized workflows and continuous learning and improvement.

These cases both demonstrate that AI not only enhances the effectiveness of existing lean tools such as Jidoka and Just-in-Time but also fundamentally drives the evolution of management thinking towards deeper data-driven decision making. This aligns with the ultimate goal of evolution of the organization through continuous improvement and learning, matching the fourteen principles. The intelligent lean system, which combines human and machine collaboration, does not contradict traditional principles; rather, it represents a transformation, with an increased focus on people and the environment in workplace. It still embodies the core idea of lean management: people-oriented and

continuously improving. Figure 5 shows the connection between case studies and basic 14 lean principles.

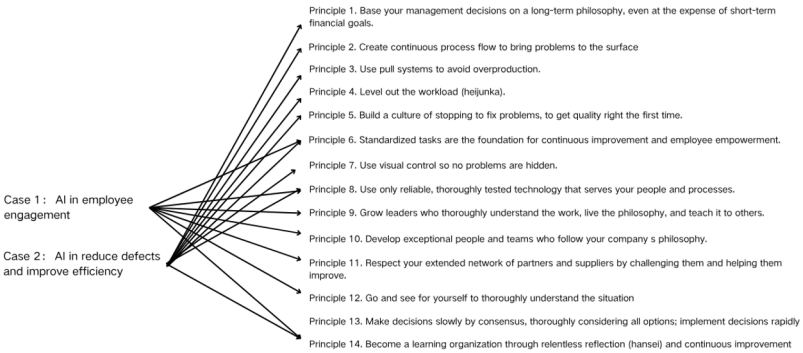

Fig. 5. Case studies with lean principles.

3.3 Discussion

Strength: These cases illustrate that the application of artificial intelligence (AI) in manufacturing, particularly in the field of lean management, has become a key driver for companies to enhance competitiveness and achieve sustainable development. In terms of quality control, AI significantly reduces human error through real-time monitoring and defect identification, ensuring product consistency; in efficiency improvement, AI predicts demand using big data and automates repetitive tasks, significantly shortening production cycles and reducing costs; regarding employee engagement, AI assists employees in complex decision-making and analysis, freeing human resources to focus on innovation and high-value tasks, while also enhancing employee skills and job satisfaction through personalized training, real-time feedback, and human-machine collaboration; in workflow optimization, AI reduces waste through automation and data analysis, expanding value stream operations to optimize workflows. Besides, the use of artificial intelligence now also pays attention to environmental sustainability and human factors. This is crucial for businesses to maintain long-term competitiveness.

Weakness: Implementing AI systems is a huge investment for companies, so relevant costs must be assessed in advance. Before integrating AI technology into a lean manufacturing system, it is necessary to confirm its compatibility with existing systems and equipment, making necessary adjustments during implementation to ensure seamless integration. Other expenditures include equipment procurement, system setup, maintenance, and operation. In addition, implementing AI technology requires substantial investments in hardware, software, and digital infrastructure, including high-performance computing devices (such as GPUs), AI platforms, data and cloud services for training and running AI models. Integration with existing enterprise systems such as ERP and CRM may face challenges of technical complexity and high

costs. If downtime or technical failures occur during implementation, it could lead to operational disruptions and decreased production efficiency.

The Cornell University team developed a cost model to estimate the training costs of personnel after the use of AI, including expenses for hardware, energy, cloud rentals, and more. The analysis shows that since 2016, the amortized costs of training compute-intensive models have been increasing sharply at a rate of 2.4 times per year. If the trend of rising development costs continues, the largest scale training runs could cost over a billion dollars by 2027,, meaning that only the most well-funded organizations will be able to provide financial support for cutting-edge AI models [9].

Opportunity: Thanks to the new technologies developed under the Industry 5.0, the manufacturing industry has made significant progress in digital evolution. Today, many countries have become more open and step forward the integration of Industry 5.0 technologies into their systems. For example, in Germany, the origin place of this new revolution, there were about 273 industrial robots per 1,000 workers in 2012. The Internet of Things (IoT), Virtual Reality, Augmented Reality, and Artificial Intelligence provide technical guarantees for the digitalization of lean manufacturing tools and principles.

A deep integration of cutting-edge technologies that improve production and operational efficiency is required for Industry 5.0. Some leader companies like Siemens and ABB, which provides digital enterprise solutions and uses robotics and automation technologies, are striving for the new area. Products such as IBM's Watson artificial intelligence platform and Bosch's IoT-enabled industrial solutions demonstrate preparation for Industry 5.0, resulting in intelligent decision-making and connected systems. In addition, some top companies that are actively responding to the changing needs of the contemporary manufacturing and industrial landscape, such as Veo Robotics, which focuses on collaborative robots, and Augury, which focuses on predictive maintenance, have demonstrated innovations that are consistent with Industry 5.0 principles [10]. All of the above-mentioned cases of enterprises and products reflect that the trend of intelligent manufacturing and Industry 5.0 is irreversible, in which automation, connectivity and data-based insights will be emphasized, thus promoting powerful productivity and creativity.

Lean principles ensure the standardization of Industry 5.0, while Industry 5.0 ensures the intelligent development of lean manufacturing tools. The implementation of lean elements is somewhat complex, which requires manufacturing companies to develop strategic implementation steps. The key opportunities that AI can provide in the field of intelligent automation in manufacturing are multifaceted and far-reaching.

Threats: Introducing AI systems in human-computer collaboration poses certain risks in terms of data security. Firstly, lean management emphasizes team collaboration and personnel allocation, but incorporating artificial intelligence into these areas may disrupt existing role divisions and workflows. Some employees have concerns about the safety of AI in practical applications; they may question the accuracy and transparency of its judgments, and managers may also doubt the fairness of AI decisions, especially when AI judgments conflict with human assessments. Another potential concern is that employees may feel undervalued and worry about being quickly replaced by AI, leading to decreased motivation or even resistance to work. When AI

provide their insights, employees must understand how to interpret its output and integrate into their workflows. If employees lack training with the AI tools, it will pose much difficult for them to use AI systems effectively. Reliable data forms the basis of AI modeling in manufacturing. For example, every time a manufacturing process is upgraded, it is important to double-check that the data fed into the AI system is accurate. Besides, data and the algorithms should be consistent with the values and short or long-term goals within the organization.

Based on the above research findings, several management insights are provided for future studies on the integration of AI and lean management: In AI implementation, managers should pay attention to the role of organizational culture. Creating a positive and harmonious human-machine collaboration environment is essential for successful AI integration. The learning requirements of each employee must be met. A personalized learning experience can enhance employee engagement and skill development, thereby improving overall performance. Significant funding is required for the technological research and development of AI, personnel training, maintenance of equipment, and other areas to achieve long-term goals. To maximize team efficiency, managers should encourage the use of AI tools to handle time-consuming tasks, allowing team members to focus on areas that AI cannot effectively address. A reasonable distribution of tasks between humans and machines can reduce waste and establish standardized processes for continuous improvement.

4 Conclusion

Artificial intelligence technology has been widely applied in the industrial sector. The outstanding performance of AI algorithms in pattern recognition, data analysis, and decision-making is used to enhance corporate performance and quality of life. The goal of lean management is to reduce waste, improve efficiency, and ultimately optimize business operation processes. Therefore, artificial intelligence has great application potential in the field of lean management. By combining keyword research from the literature and specific cases that integrate lean management concepts with AI technology, it is demonstrated that this can effectively promote intelligent and sustainable operations in the modern manufacturing and supply chain fields. As we move towards the era of Industry 5.0, this method has significant application value in key areas such as quality control and equipment maintenance management. However, managers still need to pay attention to potential risks such as high costs, inconsistencies in human-machine collaboration, and data reliability.

References

1. Varela, L., Araújo, A., Ávila, P., Castro, H., & Putnik, G. (2019). Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability. Sustainability, 11(5), 1439.
2. Tarun Rijwani, Soni Kumari, R Srinivas, Kumar Abhishek, Ganesh Iyer, Harsh Vara, Shreya Dubey, V Revathi, Manish Gupta. "Industry 5.0: a review of emerging trends and

transformative technologies in the next industrial revolution", International Journal on Interactive Design and Manufacturing (IJIDeM), 2024
3. Womack JP, Jones DT, Roos D. The machine that changed the world. New York: Rawson Associates; 1990.
4. Pampanelli, A.B.; Found, P.; Bernardes, A.M. A lean & green model for a production cell. J. Clean. Prod. 2014, 85, 19–35.
5. Tortorella, G. L., F. S. Fogliatto, A. Mac Cawley Vergara, O. Luis Gonçalves Quelhas, and R. Sawhney. 2021a. "Influence of Team Members' Characteristics on the Sustainability of Continuous Improvement Initiatives." Total Quality Management & Business Excellence 32 (7-8): 852–868.
6. Andrea Chiarini & Maneesh Kumar. (2025) Crafting a synergistic convergence: an integrated approach for lean and industry 4.0 transformation. International Journal of Production Research 63:17, pages 6493-6513.
7. Tortorella, G. L. et al. (2024) 'How does artificial intelligence impact employees' engagement in lean organisations?', International Journal of Production Research, 63(3), pp. 1011–1027.
8. Li J. Z., Herderich A., Goldenberg A. (2024, April 19). Skill but not effort drive GPT overperformance over humans in cognitive reframing of negative scenarios.
9. Cottier, B., Rahman, R., Fattorini, L., Maslej, N., Besiroglu, T., & Owen, D. (2024). The rising costs of training frontier AI models. arXiv preprint arXiv:2405.21015.
10. Rijwani, T., Kumari, S., Srinivas, R. et al. Industry 5.0: a review of emerging trends and transformative technologies in the next industrial revolution. Int J Interact Des Manuf 19, 667–679 (2025).

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