A MCDM Approach for Selection of Lean 4.0 tools in Manufacturing Sector

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***Abstract*— In today's competitive market, manufacturing organizations emphasize on producing superior quality products at the minimum possible cost to ensure customer satisfaction and continuous improvement. To enhance their competitiveness, having an effective quality management system is crucial. Quality 4.0(Q4.0) is the latest quality management system that integrates Total Quality Management (TQM) principles with Industry4.0 technologies and tools to achieve high-quality execution, superior workflow efficiency and accuracy. Lean management is another strategic approach to quality management and gaining a competitive edge in the market. It focuses on eliminating non-value-added activities and ensuring that the correct actions are taken at the correct time and place throughout every step of the production process. This approach has proven effective in addressing production-related challenges. So, integrating Lean management with Q4.0 can help the manufacturing organizations to enhance performance and competitiveness. This paper focuses on the selection of lean tools that align with the principles of Q4.0, considering sustainable criteria. By employing the Analytic Hierarchy Process (AHP), the research evaluates various lean tools from the perspective of leanness and sustainability, aiming to identify the most effective tools for modern manufacturing environments. The aim of this research work is to give useful insights to the organizations who are looking to implement sustainable lean tools in the Q4.0 era in order to optimize their operations.**

***Keywords*— Q4.0, Lean 4.0, Manufacturing, Lean tools, Analytic Hierarchy Process**

I. INTRODUCTION

In order to improve the productivity, the manufacturing organizations are continuously adopting new technologies to maintain the competitive advantage in the global market [4]. The sustainability and Lean Management are the two key approaches to remain competitive the market. Ultimate aim of these approaches is to minimize the waste and optimize the resources. In every stage of manufacturing process, the emphasis on the lean management is to implement the right action at the right time and place and removing the non-value-added activities [16]. The Toyota has adopted the philosophy of lean management and removed all the activities that did not contribute any value, after the world war 2 [35]. Lean philosophy identifies and aims to target seven types of wastes: Transportation, Inventory, Waiting, Overproduction, Motion, Defects and Overprocessing [14]. Additionally, an eighth type of waste related to the underutilization of people's skills and practical training was recognized and added to the list [33]. Some key tools used in Lean to tackle waste include-Just In Time (JIT), Value Stream Mapping (VSM),Poka-Yoke, Kanban, Kaizen, and Total Productive Maintenance (TPM). However, in order to improve manufacturing competitiveness, an effective quality management system is essential for manufacturing organizations. Q4.0 is the latest quality management system that is based on Total Quality Management (TQM) principles, which incorporates Industry 4.0 technologies to achieve enhanced performance, superior operational efficiency and accuracy [3]. Q4.0, where advanced technologies such as artificial intelligence, big data analytics and the Internet of Things (IoT) are integrated into quality management system that aims to enhance operational efficiency, product quality and customer satisfaction through data-driven decision-making and real-time process optimization [27].

Moreover, the growing emphasis on sustainability has reshaped how industries approach manufacturing processes [25]. Organizations are increasingly focused on minimizing environmental impact, reducing waste and promoting resource efficiency. In this context, lean manufacturing—a methodology originally developed to eliminate waste and improve efficiency—must be re-evaluated and adapted to meet the dual demands of sustainability and digital transformation. This research focuses on identifying the most sustainable lean tool for implementation in order to enhance productivity while being environmentally conscious. Selecting the right lean tools is crucial for improving performance in industrial sectors; otherwise, valuable management time, resources and money can be wasted unnecessarily [6]. Due to the factors like high-cost implementation and lack of expertise to make the right decision, it is necessary to choose only the most relevant lean tools [23]. The Fourth Industrial Revolution has updated and improved the lean philosophy even further by adding new modern technologies to its tools [10].

This research paper aims to explore the selection of the best sustainable lean tools that align within the framework of Q4.0. The study seeks to identify lean practices that not only enhance productivity and reduce waste but also contribute to sustainable development by minimizing environmental footprints and conserving resources. This research basically integrates lean tools, sustainability and Q4.0 in order to help organizations in achieving efficient and sustainable operations in the digital era. In order to facilitate the above issues, following research objectives are formed:

1. To identify the sustainable lean tools in the context of Q4.0
2. To identify the best sustainable lean tool in the context of Q4.0 in the manufacturing sector.

In order to achieve these above objectives, the lean4.0 tools are to be identified on the basis of leanness and sustainability criteria from a systematic literature review, the problem is a multi-criteria-decision-making(MCDM) problem. Therefore, an appropriate MCDM framework for this must be proposed. This research work utilized AHP to choose the best lean tool. The rest of the paper is organized as follows: Literature review of Q4.0 and Lean 4.0 has been covered in section II, followed by section III which presents research methodology. Results has been described in section IV followed by section V, which discusses the conclusion and future possibility of the study.

II. Literature Review

A. Quality 4.0 in manufacturing sector

Radziwill 0 defines Q4.0 as the digital advancement of all process members in order to achieve continuous improvement and sustainment. Antony 0 described it as the application of modern technologies like "Internet of Things (IoT)", "Cyber Physical Systems(CPS)" and "cloud computing" to create, manage and sustain adaptive, predictive and self-correcting automated quality systems. The main aim here is to attain higher level of productivity and operational superiority by enhancing human collaboration through total quality management. Kannan and Garad 0 explained that Q4.0 uses advanced technologies to boost production and create superior-quality products by using fewer resources. It focused on developing new production systems that meet customer needs 0. Vinodh 0 have explored how digital tools can improve the design, conformance and performance quality of products by analyzing big data. Mazzuto and Ciarapica 0 studied that technology advancements, such as affordable sensors and improved data systems, that is able to collect large amounts of data from interconnected machines. Sony 0 explained in their study the key elements necessary for successful Q4.0 implementation. They also propose developing a measurement scale and a self-assessment readiness framework to help organizations prepare for Q4.0. This data understands customer needs better and improve the balance between cost and product value. Soltanpoor and Sellis 0 studied to how that new business analytics tools provide organizations with automated, adaptive solutions to take advantage of opportunities. These tools help in quality planning, control, and improvement by offering various solutions and scenarios. Navas 0 explored another aspect of Q4.0, that is "Intelligent factory," which uses real-time data from sensors to predict quality issues and maintenance requirements. Sony 0 emphasized integrating physical and information systems, like sensors and ERP systems, to create a flexible production system. This integration improves efficiency in production. Additionally, Vinodh 0 highlighted the benefits of integrating all product-related operations to monitor quality and reliability. This integration enhanced design quality by providing better data on product usage 0. Kannan and Garad 0 explored the application of Q4.0 in integrating cyber-physical systems to identify quality issues. Sriram and Vinodh 0 examined decentralized self-organization. Implementing Q4.0 correctly, especially in manufacturing, offers significant benefits. According to Antony [3]. Q4.0 closely integrates total quality management with the principles of industry 4.0, enhancing the overall effectiveness and productivity of an organization. When applied effectively, Q4.0 boosts customer satisfaction, ensures higher-quality goods and services and offers a competitive advantage. Chiarini [11] discussed on how digital transformation has enabled the creation of advanced, data-driven manufacturing systems. By adopting these technologies, organizations can gather real-time data to monitor equipment, manage energy and perform predictive maintenance, leading to improved environmental performance and reduced energy consumption and carbon emissions. Rajput & Singh [32] studied digital transformation can also help reduce overall equipment costs and energy use, supporting a circular economy and more sustainable production.

Besides automatic data collection for preventive and predictive measures using AI software, Q4.0 practices enabled by digital transformation also include creating intelligent products by predicting market demand and consumption trends. Companies focus on customizing products as a key strategy to stand out from competitors and gain lasting competitive advantages. Oláh [28] examined in his study that how Industry 4.0 tools, using advanced internet technology and complex algorithms, assist organizations in improving operational efficiency, productivity and sustainability. As a result, businesses adopt the Q4.0 model through digital transformation to achieve sustainable excellence and the authors suggest that digital transformation directly influences sustainable excellence and links Q4.0 with it. However, there are very few numbers of studies on integrating lean 4.0 tools i.e., lean tools in the context of Q4.0. This gap necessitates integration of lean 4.0 tools in manufacturing sector

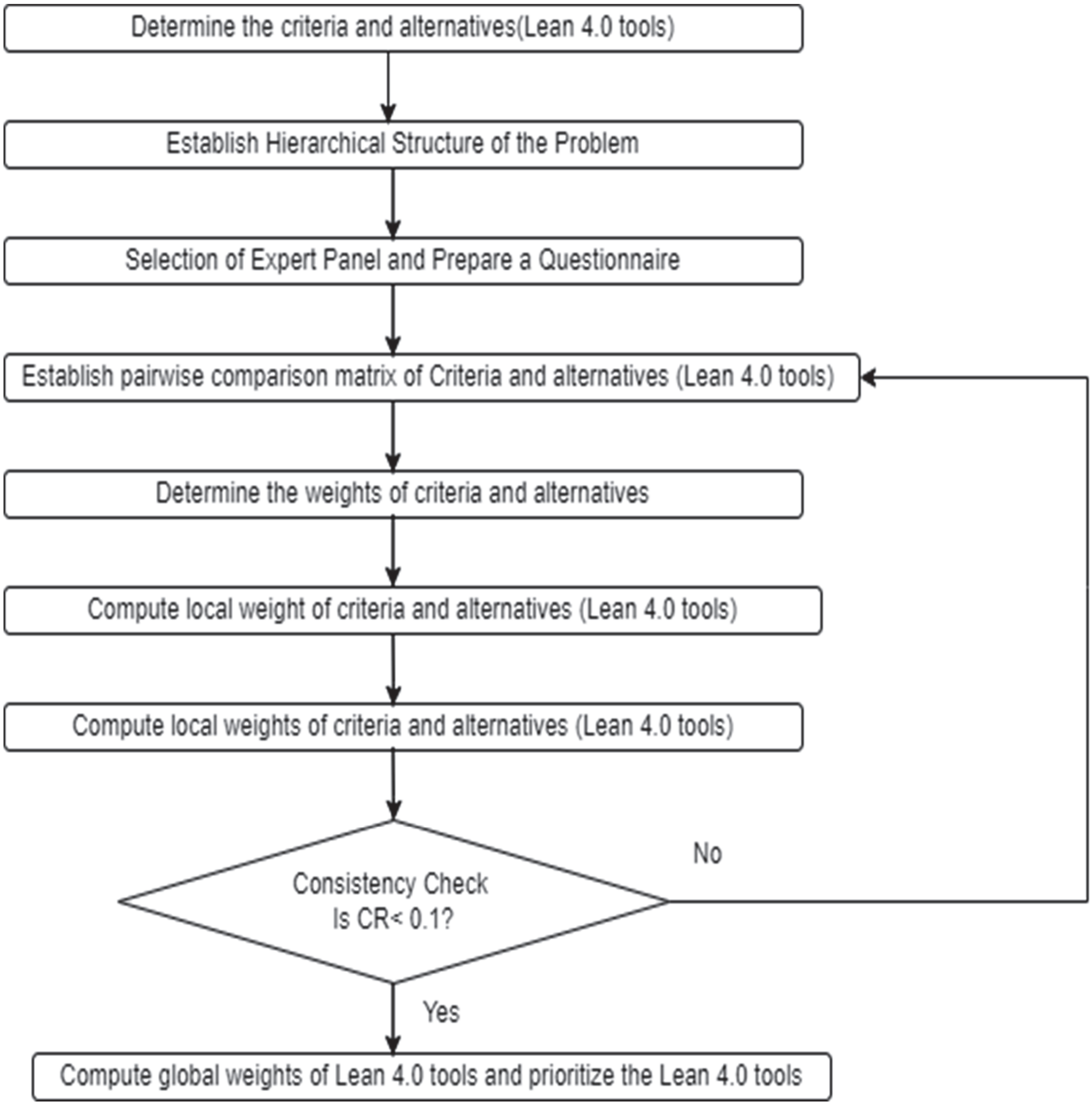
B. Integration of Lean and Q4.0

The successful strategic application of lean management, particularly in manufacturing, relies heavily on carefully selecting and applying specialized tools that guide standardized processes essential for business growth [1]. With more than 100 different lean management tools available [20], the complexity of choosing the right tools becomes crucial. It is essential to ensure that the selected tools are aligned with the specific context of the organization to achieve success.

With the arrival of Industry 4.0 Lean Manufacturing has undergone significant changes and innovations, giving rise to a fresh, digitally-oriented perspective on Lean [14]. According to a report by Alieva [2], modern technologies have enhanced the integration of Lean tools, enabling more productive improvements in the strategic planning of manufacturing industries. Bittencourt [8] suggested that Lean plays an important role in implementing Industry 4.0, focusing on Lean principles like work standardization, organization and transparency as key elements to successfully integrating digital technologies. Industry 4.0 contributes to improving Lean Manufacturing by incorporating advanced tools, which support traditional practices and help reduce manufacturing waste [33]. Mrugalska [22] explored the coexistence of Lean and Industry 4.0, suggesting that these approaches can be interconnected. They illustrate this by providing examples of intelligent products and enhanced operators focused on lean manufacturing, which shows how Lean and Industry 4.0 can complement each other. Ciano [12] highlighted that Industry 4.0 technologies have improved Lean practices by offering enhanced visibility and real-time performance data at various production stages. Ciano [12] further explored the relationship between Lean and Industry 4.0 to fully understand how these concepts interact, particularly in terms of how the digital aspects of Lean contribute to reducing performance waste associated with Industry 4.0, known as digital waste [2]. This has led to increased productivity, reduced costs and shorter waiting times. Valamede [44] described that when Lean and Industry 4.0 are combined, they create Lean 4.0, which allows them to complement each other in industry settings. So, the studies so far suggest that Lean and Q4.0 technologies can work together to enhance the identification and removal of waste in both digital and real-world processes. Nevertheless, there is still not enough research done identifying which specific Lean tools have the most significant impact in the Q4.0 context. To address this, this research work suggests a new structure to choose which Lean tools should be used in the Q4.0 setting. Additionally, this study also addresses the lack of comprehensive integration of sustainability aspects with Lean tools in Q4.0, offering solutions in this area as well.

III. RESEARCH METHODOLOGY

AHP is a widely used MCDM technique, developed by Saaty [35] used to evaluate alternatives based on various criteria. It carries out pairwise comparisons of various alternatives based on different criteria. It ensures the consistency of decision makers' inputs, which makes it unique from many other MCDM techniques. The steps involved in the AHP are described in the Fig. 1 below:



[2] AHP Methodology

IV. APPLICATION IN MANUFACTURING SECTOR

In this section, weights of the leanness and sustainability criteria, as well as the alternatives i.e., lean4.0 tools, are calculated. Hence, both of these components are evaluated independently. Based on extensive literature review and industry experts' opinions, five criteria, including "cost, quality, lead time, innovation and environmental protection" have been identified. Now, using these criteria, the lean4.0 tools, i.e., JIT4.0, Kanban4.0, Poka Yoke4.0, Kaizen4.0 and TMP4.0 are assessed to decide which tool is the most appropriate. Figure 2. Shows the hierarchical structure of AHP.

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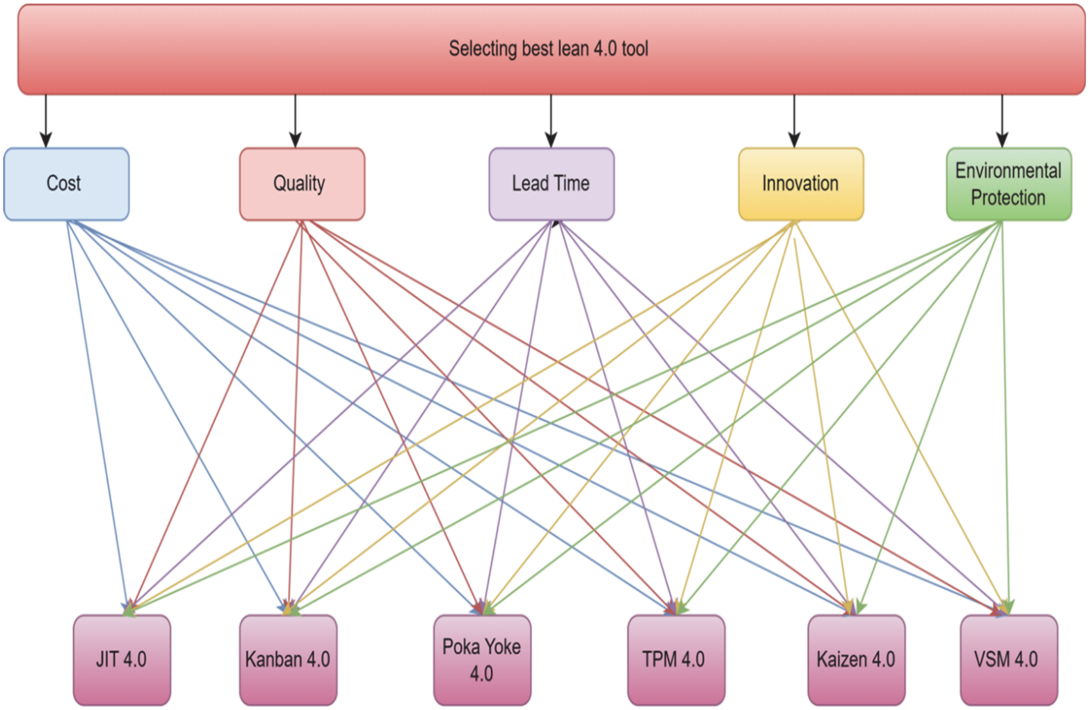

[3] AHP Hierarchical Structure

DETAILS OF EXPERTS

Experts	Experience	Area of Expertise
1	35 Years	"Sales, Manufacturing, Quality Top management"
2	30 Years	"Sales, Marketing Manufacturing Quality Top management"
3	30 Years	"Maintenance Manufacturing Method Quality Design After sales"

The calculated weights for the leanness and sustainability criteria and the lean 4.0 tools for each criterion are presented in the following tables. TABLE II presents the leanness and sustainability criteria. TABLE III contains the lean 4.0 tools considered as our alternatives. Firstly, weights of the leanness and sustainability criteria are calculated. After calculating the weights of all the criteria, the same process is followed to calculate the values for each lean 4.0 tool. Each alternative must then be compared against one another for each and every criterion. This means that this assessment must be conducted six times for each criterion. Table 6 represents the weights of leanness and sustainability criteria and the weights of the lean 4.0 tools with respect to each criterion. Finally, TABLE IV presents the final weights and ranking of the lean 4.0 tools.

CRITERIA DESCRIPTION

S.No.	Criteria	Description	Reference
1	Cost	Money or equivalent value paid for purchasing goods and services.	0
2	Quality	A feature of a product or service that shows how well it meets and goes beyond customer expectations, resulting in customer satisfaction.	0, 0
3	Lead Time	The time period between placing the order and receiving the product or service.	0, 0
4	Innovation	Innovation performance is influenced by a mix of shareholders, management and leadership, the quality of the research and development process, and the ability to innovate.	0
5	Environmental Protection	Environmental protection involves individuals, organizations and governments working to preserve and protect the natural environment.	0, 0

LEAN4.0 TOOLS AND THEIR DESCRIPTION

S. No.	Lean 4.0 tools	Description	Reference
1	JIT 4.0	JIT is a key idea in Lean that focuses on reducing waste by producing only that number of products that are needed and only when they are needed. JIT 4.0 aims to keep production smooth and responsive by tracking and managing processes in real-time, avoiding overproduction.	0
2	Kanban 4.0	Kanban was created as a simple dashboard to track the different stages that products go through during production. Kanban is used for inventory control. Kanban 4.0 is also used for inventory control and it alerts the organization for replenishment. It makes it easier for the organizations to manage their processes by providing real-time control, transparency and better integration with stakeholders. It also allows automatic ordering between customers and suppliers.	0
3	Poka Yoke 4.0	Poka yoke is a Lean tool which aims at preventing errors and minimizing mistakes in the processes. Poka yoke 4.0 improves this further by enabling machines to continuously check products during production to spot any issues right away.	0.
4	TPM 4.0	It is a lean tool that helps in the maintenance of machines and ensures no unexpected breakdowns and waste. TPM 4.0 uses predictive maintenance to predict when machines need repairs before they fail. It uses digital technologies like IoT, Big Data, Cloud computing, automated robots and augmented reality to monitor machines more accurately hence saving time and resources.	0.
5	Kaizen 4.0	Kaizen aims at continuous improvement. Kaizen 4.0 aims at enhancing employees' digital skills and collaboration between robots and people.	0.
6	VSM 4.0	VSM is used to map out key areas in production processes, helping to identify issues, bottlenecks, and areas for improvement. VSM 4.0 enhances this further by enabling real-time monitoring of value flows within and outside of organizations. This real-time data allows companies to connect with stakeholders inside and outside the organization, with the ability to access information remotely at any time.	0.

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FINAL WEIGHTS

S. No.	Criteria	Weights	JIT4.0	Kanban4.0	Poka Yoke4.0	VSM4.0	Kaizen4.0	TPM4.0
1	Cost	0.2542	0.2367	0.0860	0.1160	0.2108	0.2109	0.1393
2	Quality	0.2266	0.2432	0.0902	0.1083	0.1136	0.2603	0.1840
3	Lead time	0.0656	0.3360	0.2375	0.1222	0.1088	0.1088	0.0864
4	Innovation	0.0375	0.3950	0.2241	0.0978	0.0666	0.0576	0.1585
5	Environmental protection	0.4157	0.0761	0.0494	0.3169	0.2738	0.1452	0.1384

FINAL RANKING OF LEAN 4.0 TOOLS

S. No.	Lean 4.0 tools	Final Weights	Rank
1	JIT 4.0	0.1839	3
2	Kanban 4.0	0.0869	6
3	Poka Yoke 4.0	0.1975	2
4	VSM4.0	0.2029	1
5	Kaizen 4.0	0.1823	4
6	TPM 4.0	0.1463	5

V. RESULTS

TABLE VI shows the final ranking of lean 4.0 tools while incorporating leanness and sustainability criteria. VSM 4.0 ranked highest, making it the most critical tool. VSM 4.0 enables the manufacturing industries to consider their entire value stream of a product and identifies wastes, bottlenecks and scope for improvement. Poka Yoke 4.0 came in second, highlighting its role in preventing defects and ensuring quality. JIT 4.0 ranked third, which shows its capability of reducing waste and increasing efficiency by delivering products exactly when required. Kaizen is placed fourth, which aims at continuous improvement. TPM 4.0 ranked fifth, stressing on its importance of improving the efficiency and safety of production equipment. Kanban, placed sixth, which focuses on workflow and inventory. These rankings provide the organizations with the strategic framework to incorporate sustainable lean tools in the context of Q4.0.

VI. CONCLUSION

This research proposes a framework to select the lean 4.0 tools by considering the sustainability criteria. Various Lean tools are evaluated and ranked based on their effectiveness in improving

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operational efficiency, quality and sustainability in today's manufacturing organizations. This evaluation is done by using AHP technique. This study provides a strategic framework for manufacturing organizations to select and implement sustainable lean tools that are aligned with Q4.0. Organizations can enhance their productivity, minimize costs and maintain a competitive edge in the digital era by incorporating the lean 4.0 tools. The future scope of this research can be performing a similar study using other Multi-Criteria-Decision-Making (MCDM) methods. Furthermore, similar research can be conducted by considering a specific industry case study.

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