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Integrating Lean Principles into Lean Robotics Systems for Enhanced Production Processes

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Abstract: Integrating lean principles into lean robotics systems emerges as a transformative path for production processes. This paper addresses the question of what are the best practices of integrating lean principles within robotics systems to enhance production processes in manufacturing systems through a comprehensive literature review, direct engagement with robotics engineers, and generating a Voice of Use Table Performance analysis (VOT) and Key Performance Indicators (KPIs) to illuminate the advantages realized from lean principles within robotics systems and draw attention to the current gap of how robotics systems can become lean in manufacturing to maximize their value in production processes. The paper focuses on the key findings of the possible influence on the development of the principles of lean, as well as the precision and accuracy of robotics systems for improved production processes in manufacturing systems.

Keywords: lean robotics systems; lean manufacturing; lean principles; focus study; voice of table performance

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1. Introduction

The field of robotics is becoming more important to industries as a result of numerous incentives, such as reduced cost, improved product quality, and performance. These enhancements are manifested in both manufacturing and service industries. Lean robotics is a concept that integrates the philosophy of lean thinking into robotics development in order to assess the performance of the robotic system using performance indicators that mirror the principles of lean thinking.

On the other hand, lean manufacturing systems aim to enhance efficiency, reduce waste, and optimize production processes. Building on this idea, lean manufacturing is an efficient way to identify and eliminate waste through incessant improvement [1]. As a modern industrial operation, the lean manufacturing system represents a unique solution to transform manufacturing processes in the direction of efficiency, increasing productivity and maximizing quality in producing goods by focusing on waste elimination and cutting the non-added value and reducing the production cycle [2,3].

At its core, the lean manufacturing approach relies on tools like Kaizen, Just-In-Time (JIT), Value Stream Mapping (VSM), and Total Productive Maintenance (TPM) and requires changes and operational shifts within organizations [4].

The journey towards perfection in manufacturing systems is full of challenges from the complexity of technical implementation and the integration of modern technology for automating processes. For instance, "GIANT" used industry 4.0 to build a platform to interact with customers as a lean smart manufacturing between the development and

the business [5]. This improvement in manufacturing processes underlines the impact of digital technologies for more agility and customer satisfaction by raising productivity and lowering the total downtime [6].

However, lean principles, known as the Toyota Production System (TPS), are considered the guidelines of lean manufacturing that aim to improve efficiency, eliminate waste, and create value in production processes. Adding to this perspective, the most well-known definition of lean principles passes through some major ones depending on value management. The first lean principle and the basis for all following principles is to specify the value as defined by the customer of the particular enterprise [7].

One of the key strategies of lean principles is to focus on small batch sizes in production processes. This key organizes several lean concepts, such as establishing pull systems, improving flow, and considering humans' roles [8].

In the context of modern technology, lean methodologies focus on the smart implementation of processes and systems, which is crucial for effective deployment. As described, before implementing smart technologies, managers are advised to focus on implementing lean principles. Specifically, if they plan to implement MES systems, the presence of lean principles is needed. And if they aim for full presence of smart technologies, then high levels of lean principles are required [9].

By way of explanation, it is evident that lean principles are a set of concepts that were developed to be applied across diverse processes and industries in manufacturing systems to eliminate waste, increase efficiency, and create value for the customer. However, in industrial automation, lean manufacturing systems have extended their technological advancement and robotics to create lean robotics systems as an integration between the principles of lean and robotics systems to further increase efficiency and productivity in manufacturing processes.

The purpose of this paper is to link the implementation of the robot with the principles of lean thinking in order to improve the performance of the entire robot system to enhance production processes in manufacturing systems by finding the best practices of this integration and creating the key performance indicators to track improvements and performances where organizations can strategically utilize them to increase productivity, reduce cost, enhance accuracy, and shorten cycle time processes. The assumption can be scratched and turned into profit by determining what the consumer is willing to give while working without defects. Verifying this idea in accordance with the book *Lean Robotics: A Guide to Making Robots Work in Your Factory* by Samuel Bouchard considers that "lean robotics will provide you with tools to make the process more efficient. A more efficient cell deployment project will be more cost-effective and provide a higher ROI". Hence, lean robotics systems should be the core piece of industry within international competition.

In introducing the subject of the gap between how lean principles are applied to robotic systems and what the primary functions are in which robotics systems are considered lean in manufacturing processes, on many occasions, when deploying robots, industries focus on industrial efficiency in terms of being lean and the goals of deploying robots for increased capacity and better speed of operation. Among best practices in this context, investing in additional robotics systems that specialize in high-volume products is appealing to satisfy all customer needs in a comprehensive manner.

This study results in the power of merging the two approaches in manufacturing processes in all forms, including the robot's context, especially with the accuracy and the speed of robotics systems that can offer new skills to operate and maintain precise production processes and swiftly respond to the changing of customer demands to meet individual needs. As described, "improving the capacity for adaptability and flexibility of robotic systems within manufacturing is seen as both a key indicator of the level of a

system's intelligence and provides a solution for overcoming the performance disparity within human-machine interaction, mitigating the effect on the system" [10].

2. Materials and Methods

The research methodology explored in this study is a multidimensional technique combining literature review, focus group discussion, and Voice of Table (VoT) analysis. Each method was chosen for its strength, ensuring a comprehensive exploration of the integration between lean principles and lean robotics systems following the steps below:

(a) Understanding lean principles in manufacturing systems is an initial step that serves as the basis of reviewing the existing literature on lean principles in manufacturing systems. The importance of this method offers insights and potential gaps in the current knowledge. The literature review includes articles from the years 2013 to 2024, along with two articles from 2011 and 2012 on lean robotics, lean manufacturing, and lean principles, ensuring an analysis of the latest knowledge.

The factors taken in this step consider case studies implemented in manufacturing systems to enhance production processes' performance. These factors include the examination of lean tool implementation, the combination of lean principles, and the development of lean product development principles, as well as the material flow based on articles collections.

This area of this research outputs the functions based on understanding lean principles in manufacturing systems through (a) finding the missing gaps in organizations and production plans and (b) locating a place where the robot can be applied in manufacturing applications.

(b) Focus Group Discussion. Robotics engineers are responsible for deciding the best possible solution that can be used to solve the automation problem. This step has recognized the results of integrating lean concepts into robotics systems by contacting directly robotics engineers, delving into their day-to-day activities and challenges. This approach was able to bridge the gap between theory and practice, exploring real-world applications and the potential barriers to integration, and it has examined the advantages of integrating lean principles into robotics systems for improved production operations based on a survey related to the incorporation of lean principles into robotics systems. There were a variety of questions, some with numerical scales and others with text-based responses. The data were analyzed in two steps, with the first step representing the quantitative analysis (numerical answers) as they can be visualized through graphical representations such as histograms and qualitative analysis for textual responses.

This phase was able to define the production process resilience in the face of disruptions through the relationship between the application of lean principles in robotics systems and production process resilience by providing examples of how lean principles have contributed to improving production process resilience.

This focus study outputs the main rules to make the robotic system lean and functional in manufacturing systems, and it creates the ideal functions that are particularly important for improving the resilience of specific types of disruptions, such as internal disruptions like equipment failures or quality control, and external disruptions like the supply chain in market dynamics, which will support addressing the best practices of integrating lean principles within robotics systems to enhance production processes in manufacturing systems.

(c) The role of robotics systems will discuss the advantages of deploying robotics systems in manufacturing applications, and understanding the progress of traditional robotics

systems to be leaner and adaptable through a structured approach begins with the definition of lean robotics systems, the historical context of robotics systems, the technological advancement of lean robotics systems, and the lean principles applied in robotics systems.

The output of this step represents the key indicators of lean robotics systems and the modern technologies applied in robots against the previous ones. Creating the important functions of merging the two approaches in manufacturing processes offers new skills and practices that operate and maintain precise production and fast implementation.

(d) Voice of Table Performance Function Deployment (VoT) analysis. Based on the insights gathered from the previous steps, the VoT analysis represents the synthesis tool by identifying the primary functions and scopes that act as a conduit to determine the pathways in integrating lean principles into lean robotics systems. In this context of industrial collaborations, it facilitates the development of lean robotics design aimed to validate potential skills and practices in terms of interruption, quickly adapting to changes, eliminating unnecessary motions, cost savings, and more. The proposed approach can thus be used to assess the performance of different configurations of robotics solutions. This brings together new techniques relating to robotics and manufacturing, leading to advanced manufacturing systems, which in turn offer safer working environments, more optimized operations, and better end user products. Moreover, it assists researchers in identifying the best aspects of lean integration in robotics while offering a fine view of how and where the most frequent research questions are raised.

3. Understanding Lean Principles in Manufacturing Systems

Lean production systems, or lean manufacturing, are concepts of management applicable in many industry sectors that describe production processes as defined under the lean concepts [11]. The main principles of lean are the reduction of the seven wastes, or Muda, described in Figure 1. Taiichi Ohno, the co-developer of the TPS, emphasized that the portion costs in non-lean manufacturing environments are attributed to various forms of waste. The identified forms of waste are as follows:

- Transportation: refers to unnecessary movements of products, materials, and data from the process flow, leading to delays and increases in cost;
- Inventory: describes the raw materials, finished goods, and work-in-progress. As a result, excessive inventory will lead to reduced flexibility and increased costs;
- Motion: refers to unimportant steps by workers and equipment during the process flow, which reduces productivity;
- Waiting: indicates the idle time in the process flow while no value was added, leading to decreased efficiency and productivity;
- Overproduction: the process of producing goods and products more than what is required by the customer, which will add more complexity;
- Overprocessing: adding more complexity and doing more work to a product or a process that is unnecessary to meet customer needs;
- Defects: clearly points to defects, errors, or rework in the production, resulting in customer dissatisfaction, potential rework, and higher expenses.



Figure 1. The seven wastes.

The implementation of lean production systems is based on continuous improvement and involvement of all staff. Although the benefits of implementing lean principles are well known around the world, it remains a challenge when incorporating these aspects into automated systems [12]. On top of that, lean principles defined in manufacturing systems by James Womack and Daniel Jones are described in Figure 2. The principles of lean in manufacturing systems:

- Specify Value: which describes the customer's need;
- Identify value stream: identifies all processes from producing to delivering to the final customer;
- Create flow: ensures the process flows smoothly with no interruption;
- Establish pull: refers to "time to market", which means the customer can pull the product from manufacturing as needed;
- Pursue perfection: make lean thinking a part of the corporate culture.

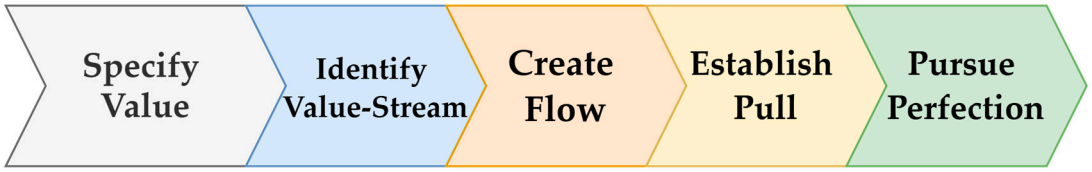


Figure 2. The principles of lean in manufacturing systems.

To learn more about how technological advancements emphasize these principles, it is necessary to understand the foundational aspects of lean production. The primary principle of lean production is the elimination of waste at the organization's level, while the ultimate goal is value creation that allows companies to achieve this business principle.

The fundamental principles for the culture of continuous improvement help manufacturing practices evolve to be just-in-time and built-in quality.

JIT is a manufacturing philosophy based on producing goods. JIT is basically aimed at producing a product only in the required quantity, at the required time, and rejecting anything that is not ordered.

Continuous improvement is the backbone of lean thinking. It refers to the permanent and ongoing improvement of all processes regarding service, product, marketing, or administration. Robotics and automation are possibly the most frontier technologies that have brought lean production one step ahead. Robotic devices may be found in many applications, ranging from coating tasks to assembly operations and quality control methods.

Figure 3: The logical relationship among the frontier technologies of lean production provides a comprehensive framework that shows three main categories—digital twins, smart manufacturing, and sustainable lean practices—which demonstrate the logical connections between lean production and technological advancements. Lean production is the primary concept of this figure that prioritizes waste elimination, efficiency improvement, and value creation. Each of the technological advancements—digital twins, smart manufacturing, and sustainable lean practices—represents unique benefits while facing distinct challenges.

Digital twins represent virtual replicas of real-world systems. Real-time data connections and comprehensive modeling of production processes make it possible. These digital models enhance agility and precision by providing insights that bridge the gap between physical and digital entities. The successful implementation of digital twins depends on addressing some technical challenges like integration complexity, data management, and the need for highly skilled engineers.

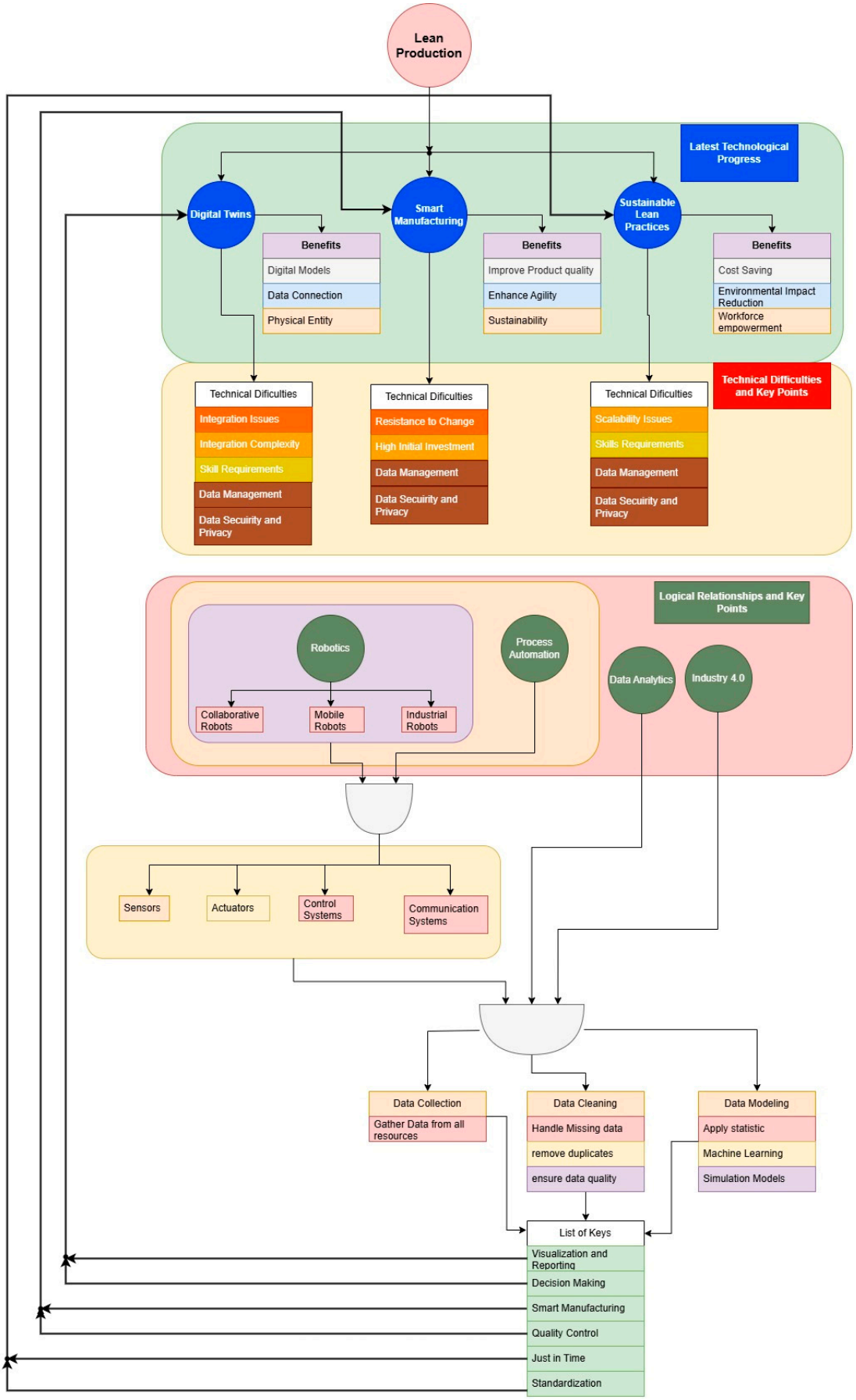


Figure 3. The logical relationship among the frontier technologies of lean production.

Smart manufacturing incorporates advanced technologies such as automation, data analytics, and Industry 4.0 frameworks. This technical approach promotes sustainability in production systems, improves product quality, and enhances operational agility. Notwithstanding these benefits, challenges such as high initial investment, resistance to organizational change, data security concerns, and privacy are presented as barriers.

Sustainable lean practices focus on aligning lean concepts with environmental and economic sustainability. These methods seek to deliver cost savings, minimize the negative effect on the environment, and empower the workforce. However, major obstacles to achieving these advantages, like lack of skilled labor and data security concerns, keep showing up.

The integration of these technological advancements with enabling tools and systems is further depicted in the figure. Robotics and process automation, supported by components such as sensors, actuators, control systems, and communication networks, play a central role in optimizing operations. Collaborative robots, mobile robots, and industrial robots are presented as key contributors to achieving efficiency, precision, and safety in manufacturing processes. Additionally, real-time data for ongoing process optimization, data analytics, and Industry 4.0 technologies improve decision-making.

At the bottom of the figure, the data-driven process required for successful lean production takes center stage. Data collection from multiple sources is the first step in this process, which is followed by data cleaning to ensure accuracy and quality. Finally, data modeling uses technologies like machine learning, statistical techniques, and simulation models to transform information into action. Critical applications like visualization, reporting, decision-making, and implementing lean principles, such as just-in-time production and standardization, are all supported by these findings.

Considering the selection of articles addressed on lean manufacturing systems, Table 1. Summarizing case studies/examples of lean manufacturing systems based on article collection has been generated to summarize the various case studies where lean manufacturing principles have been successfully implemented. This table provides a demonstration of various applications of lean manufacturing systems across different industrial sectors, such as the Large Polish Factory (Mirages of Lean Manufacturing in Practice) [13], GIANT (Lean Smart Manufacturing in Taiwan) [5], Coca-Cola HBC Russia's Warehouse (Improvement of Warehouse Logistics) [14], Marine Company's New Thruster Project (Using Lean to Transform PD Process) [15], SME Real-Time Monitoring (Real-Time Monitoring System to Lean Manufacturing) [6], Jaguar Land Rover Engine Manufacturing Centre by McKie et al. [16], Impact Footwear [17], and Digital Lean Manufacturing Course at SIIT [18].

The case studies highlight the fundamental ideas of lean manufacturing systems, emphasize several difficulties, and show how understanding the unique circumstances of each company incorporating technology and concentrating on continuous improvement can lead to successful outcomes. However, it is important to expose gaps and opportunities identified for aspects of integrating lean principles in manufacturing and production concepts in advance for building robotics systems frameworks. Thus, the current section proposes a categorization of contributions on related topics. After conducting an extensive review of the case studies, the following will be accomplished by integrating lean principles with the deployment of robotics systems:

- Overproduction: in robotics, through precise programming and synchronizing, robots will manufacture an accurate quantity of needed goods;
- Waiting: involves robots operating continuously through effective maintenance and continuous improvement among different parts of the system;

- Transportation: in a robotic context, transportation refers to an efficient routing of materials or products between the robotics stations, leading to an optimized time and reduced risk of damage;
- Motion: includes an efficient and precise pattern or sequence that adds value, eliminating unnecessary adjustments through optimization;
- Defects: such as early detection of defects and minimizing the need for rework or scrap.

Table 1. Summarizing case studies/examples of lean manufacturing systems based on article collection.

Case Study	Goal	Lean Solution	Implementation
Large Polish Factory (Mirages of Lean Manufacturing in Practice)	Understanding why lean tools did not achieve expected waste elimination despite high implementation levels	Examination of lean tool implementation	Analysis of employee involvement, management approach, and cultural aspects in lean tool effectiveness
GIANT (Lean Smart Manufacturing in Taiwan)	Implementation of lean smart manufacturing, integrating lean production with Industry 4.0	Combining lean production principles with Industry 4.0 technologies	Gradual build-up of lean smart manufacturing, focusing on customer interaction and co-creative platforms
Coca-Cola HBC Russia's Warehouse (Improvement of Warehouse Logistics)	Enhancing warehouse logistics through lean manufacturing principles and digital technologies	Application of digital technologies to lean principles in warehouse operations.	Introduction of mechanization and digital technologies to improve efficiency and reduce costs
Marine Company's New Thruster Project (Using Lean to Transform PD Process)	Evaluating the effectiveness of lean product development in marine product development	Implementation of lean product development principles	Integration of manufacturing competencies early in the product development process
SME Real-Time Monitoring (Real-Time Monitoring System to Lean Manufacturing)	Enhancing lean manufacturing processes in SMEs through real-time monitoring systems	Integration of real-time production monitoring systems	Tailoring real-time monitoring to SME needs, balancing technology with lean principles
Jaguar Land Rover Engine Manufacturing Centre	Implementing digitalized lean manufacturing training during the COVID-19 pandemic	Transition to online training platforms and digital resources	Development of digital training materials and assessments, adapting to remote and socially distanced learning environments
Impact Footwear	Customizable product development	Mass customization and design efficiency	Utilized AM for on-demand manufacturing of customizable slippers
Digital Lean Manufacturing Course at SIIT	Equip students with lean manufacturing skills using Industry 4.0 methodologies	Combination of theoretical education and practical training in lean manufacturing and Industry 4.0	Development and offering of a comprehensive course that includes simulations, project-based learning, and collaboration between university and industry

The conclusions carry a call to make additional technological advances, turning general research pointers into actionable opportunities. The present research charts an expanded role and, at the same time, autonomously reviews the content of the literature on an area

of intersection to find the missing gaps in organizations and production plans to locate a place where the robot can be applied in manufacturing applications to ensure that robotic operations are more effective, adaptable, and robust in manufacturing systems. Addressing the functions (F1) decrease in interruption, (F2) quality control, (F3) speed up production process, and (F4) decrease waiting requires careful design, programming, maintenance, and continuous improvement; thus, the implementation of the robotic cells will favor the productive flow. In case of any production change caused by an unforeseen problem, the system must be able to adapt and respond to the variations of specifications and quality. In production lines using robotics, the simple inclusion of the robotic cell causes an increase in work in progress, as the production of the robot cells is normally carried out in batches, and there is a likelihood of not being able to respond to the changes in other stages of production, causing high material stock. It is with the integration of lean principles with lean robotics that work in progress can be significantly reduced as the robotic cells are inserted in the production line of small and medium enterprise manufacturing companies with specific production needs [19,20].

4. Direct Engagement with Robotics Engineers

Projects can be developed in which the ideas regarding improvements and innovation are transmitted to the engineers through a very close partnership in direct contact with them. This can be realized through the suggestion boards that are frequently part of lean lines, using a more direct manner in continuous improvement projects and in other forms of project implementation. The robotics engineers evaluate the necessary actions and techniques to perform a robotic solution with the best precision and within the customer's desired cycle time, leading to better automated manufacturing systems, particularly in cases where customers' needs are flexible. This direct engagement/focus study with robotics engineers was crucial as automated manufacturing systems continue to expand. This ensures the real issues are faced by companies in their future development. Table 2: The survey's questions and the approach used for each set demonstrates the survey's questions and the approach used for each set, discovering that the survey encompasses a wide range of lean concepts and lean robotics systems, starting with lean principles in robotics systems, rating of lean principles and robotics systems, production process resilience, lean principles and resilience, and implementation and challenges. Their overall objectives were to develop their own unique entry-level ideas and to gather data on robotics users of an improved lean robotics system in order to attract a lot of attention and build on their reputation for delivering innovative manufacturing solutions and to automate tasks to enhance the precision of manufacturing processes. The objectives of this survey are to be associated with specific high-tech robotics engineers to take all the capability that enables the root of engineering solutions to develop faster and less complex robotics systems, which leads to lower customer costs, to design more reliable systems that match the corporate objectives, and to search for an innovative robotics solution so that manufacturing processes struggle less, especially where the demand is changing rapidly, and production is required to become more flexible. The need is to be able to adapt to high variance and instability in different hard and soft factors related to the production system. In this light, the creation of this discussion is able to provide all the advantages of new lean production systems improved by lean robotics systems.

Table 2. The survey's questions, and the approach used for each set.

Case Study Approach	Survey Questions
Respondent information	What is your role in the organization? How many years of experience do you have in the industry? What type of industry does your organization belong to? How would you define "lean principles" within the context of your organization? To what extent are lean principles being incorporated in your organization's robotic systems?
Lean Principles in Robotic systems	Can you list the lean principles that are most important in the context of your organization's robotic systems? How are these lean principles incorporated in the design, development, and operation of your robotic systems? How is the effectiveness of lean principles measured in your organization's robotic systems? How has the application of lean principles improved the efficiency of your robotic systems? On a scale of 1–5, how well are lean principles incorporated in your organization's robotic systems? (1 = Not at all, 5 = Fully incorporated) On a scale of 1–5, how would you rate the effectiveness of lean principles in your organization's robotic systems? (1 = Not at all effective, 5 = Extremely effective)
Ratings of Lean Principles and Robotic Systems	On a scale of 1–5, how much has the application of lean principles in robotic systems contributed to the elimination of waste and increased efficiency in your organization? (1 = No contribution, 5 = Significant contribution) On a scale of 1–5, how much has the application of lean principles in robotic systems contributed to continuous improvements in your organization? (1 = No contribution, 5 = Significant contribution) On a scale of 1–5, how easy is it to reconfigure and reprogram your organization's robots when introducing new products into the manufacturing process? (1 = Extremely difficult, 5 = Extremely easy) How would you define "production process resilience" within the context of your organization? On a scale of 1–5, how would you rate the importance of production process resilience in your organization's operational strategy? (1 = Not at all important, 5 = Extremely important)
Production Process Resilience	On a scale of 1–5, how resilient do you consider your organization's production processes in the face of disruptions? (1 = Not at all resilient, 5 = Extremely resilient) How do you assess and improve the resilience of your production processes? Can you give examples of how your organization has demonstrated production process resilience in the face of disruptions? Do you see a relationship between the application of lean principles in robotic systems and production process resilience? Can you provide examples of how lean principles in robotic systems have contributed to improving production process resilience? In your view, what lean principles contribute the most to production process resilience?

Table 2. *Cont.*

Case Study Approach	Survey Questions
Lean Principles and Resilience	Are there any lean principles that you think are particularly important for improving resilience in the face of specific types of disruptions (e.g., supply chain disruptions, equipment failure, etc.)? On a scale of 1–5, how much do you think the application of lean principles in robotic systems contributes to production process resilience? (1 = No contribution, 5 = Significant contribution) On a scale of 1–5, how well has the application of lean principles in robotic systems improved your organization's resilience in the face of specific types of disruptions (e.g., supply chain disruptions, equipment failure, etc.)? (1 = Not improved at all, 5 = Significantly improved) What challenges have you encountered in applying lean principles to robotic systems? What are the barriers to improving production process resilience in your organization?
Implementation and challenges	On a scale of 1–5, how complex do you find the implementation of robotic systems in your organization? (1 = Not at all complex, 5 = Extremely complex) On a scale of 1–5, how important is providing training after implementing robotic systems in production processes? (1 = Not at all important, 5 = Extremely important) Do you have any suggestions on how to better integrate lean principles in robotic systems to improve production process resilience?

The outcome was very pleasing, which illustrated that deploying robotics systems will reduce system error probabilities, which leads to good things from a business perspective. Decreased errors shorten lead times and reduce production losses and costs, ultimately reaching the customer in the form of a lower price. This might include cut-off disruptions across organizational units and more inclusive, longer-term technological solutions leading to improving the work environment. To achieve a successful lean robotics integration, senior leadership should be clear on the scope of the touchpoints, and it is highly recommended to involve the front-line associates in robotics' continuous improvement, mapping waste to develop a clear vision and provide the means and resources to accomplish the task.

Figure 4: The current status of lean concepts incorporated into robotics systems provides the current status of lean concepts incorporated into robotics systems utilizing data from the focus study represented through a series of histograms. Each histogram is designed to illustrate a category on X-axis and a count on Y-axis. These categories are based on the responses gathered, where the participants were asked to rate their answer on a scale ranging from 1, representing "Not at all" to 5, which signifies "Fully/Extremely", as follows:

- **Lean principles incorporation:** The histogram shows a concentration around the mid-scale. This indicates how lean principles are incorporated into robotics systems, and it implies that there is still room for improvement in organizations, while others have already integrated lean principles into their manufacturing systems;
- **Resilience consideration:** These data illustrate the resilience of lean robotics systems. A higher rating implies a perception of resilience and suggests a diverse range of experience and a possibility of the need for more robust systems;

- **Applications of lean principles eliminate specific types of disruptions:** These data illustrate how lean principles are applied in robotics systems, how well they work in recovery from disruptions, and how it is important to adopt lean principles;
- **Contribution of continuous improvement:** The positive impact of improvement and efficiency is determined by the histogram. It demonstrates how much the implementation of lean principles has contributed to continuous improvement;
- **Ease of integration:** The histogram indicates that there are common challenges observed, and it measures how simple it is to integrate lean concepts into robotics systems and highlights factors that are important for a successful adoption of lean principles;
- **Importance of training:** The histogram reflects how important it is to provide training on lean robotics applications. The need for training is demonstrated by the higher ratings towards the upper end of the scale;
- **Complexity of implementation:** The data show how complex it is to implement robotics systems. The histogram demonstrates that the systems are found to be less complex by integrating lean principles into robotics systems.

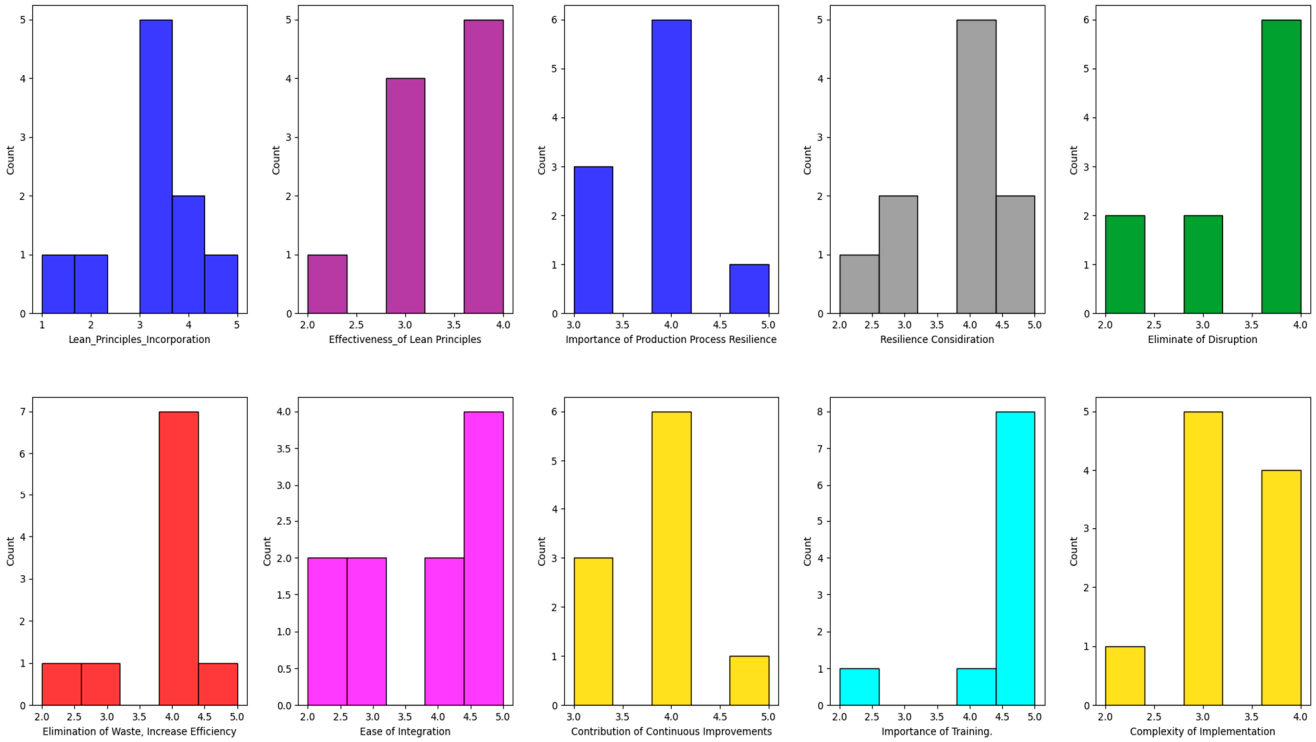


Figure 4. The current status of lean concepts incorporated into robotics systems.

Participants have provided different definitions of lean principles, and they have mentioned some concepts like flexibility and adaptability. They demonstrated strategies such as continuous improvement, standardization, and fast development. Nonetheless, some feedback indicated that lean principles are being incorporated into many contexts, including robots. Some organizations applied lean principles in all aspects, while others are still in the process of structuring their approach. Robotics does have limitations; there are going to be challenges in integrating lean principles with robotics, such as overcoming technological limitations and overcoming resistance from workers and management, while the struggle of maintaining an organizational culture is identified as a barrier. Other participants indicated that educating and training teams on lean principles and emphasizing the importance of people management are recommended for less complexity.

In this discussion, there were several assessments made of how lean and robotics can be further integrated into organizations' operations. Lean robotics knowledge should be constantly evolving and adapting. Particularly in the context of robotics systems, the first step is to create value, which means that products are produced to customer requirements with minimum lead time. The most successful application for robotics is when they perform repetitive tasks. Mapping out knowing where non-value time was spent can help in focusing on what processes need improvements from a robotic perspective so that, addressing the functions (F5) eliminate unnecessary motion, (F6) eliminate non-value added, and (F7) product mix would be seen as a growing future trend as this system learns and adapts to change, being key to success. In particular, the promise of robotics is precision, and as multiple independent robotic systems deliver their goods with minimal variation in process parameters, the result is automated assembly or any manufacturing process with components or products being identical. Robotic system manufacturers therefore develop systems with extremely high integrity and precision to ensure full use of the robots' throughput capacity.

5. The Role of Robotics Systems in Manufacturing

"A robot is a complex mechatronic system enabled with electronics, sensors, actuators, and software, executing tasks with a certain degree of autonomy. It may be preprogrammed, teleoperated or carrying out computations to make decision" [21]. In the field of robotics, the word "**robot**" was expanded to describe machines that perform tasks. Nevertheless, the beginning of industrial robots was marked by George Devol's creation of the first programmable robot called Unimate in 1956. His design was based on hydraulic actuators. In 1961, the deployment of industrial robots took place at the General Motors plant in New Jersey. The use of robots grew widely in the automotive industry from 1970 to 1980 for tasks such as painting, assembly, and welding. However, the introduction of the PUMA (Programmable Universal Machine for Assembly) robot by Unimation with General Motors was in the 1980s. Robots were able to carry out complex and dangerous tasks by integrating the advancements of AI and ML in the 2000s; additionally, the integration of collaborative robots and AI appeared in the 2010s, which deployed a fully robotic cell that can learn from its environment. Lean robotics systems originated from the intersection of lean principles and manufacturing systems. The history of lean robotics systems needs to explore the development of robotics and the advancement of cutting-edge technologies. Some authors discussed the starting point of the term "lean robotics systems", prior 1994, the concept of combining lean and robotics was unknown. The term was referred as "Lean Robotization", later, in 2007, as a part of a research, for lean and robotics, the phrase "Lean Robotics" entered the lexicon [22]. The number of publications from 1994 until 1997 was identified as up to three publications. And between 2007 and 2011, five publications were identified, increasing to eight publications between 2017 and 2019. In contrast, from 2020 until 2022, the number of publications increased to 12, highlighting the advancement in lean robotics systems [22]. The world robotics report 2023 shows that China is still the best player in the world from the total installed robots, up to 290,258 units, followed by Japan, up to 50,413 units; the United States; the Republic of Korea, up to 31,716 units; and Germany, up to 25,636 units.

The lean robotics methodology offers a sustainable way to cut waste and boost a business's productivity by using lean manufacturing principles to implement robotic automation [23]. In contrast, authors consider that "LR is therefore a modern approach to the robotisation of production, wherein the production process is carefully considered and analysed" [24]. Robots play an important role in manufacturing systems because of the benefits they can provide, such as reducing waste and speeding up the production

processes. However, Figure 5. Core ideas from lean robotics and automation frameworks demonstrates the core ideas from lean robotics and automation frameworks to emphasize the importance of human safety, robotic performance optimization, waste elimination, and utilizing the combined strength of humans and robots. The following are the primary elements of lean:

- **"People before robots"**: it considers human safety when implementing a robotic system in manufacturing processes, which includes enhancing the work environment and increasing the collaboration between humans and robots;
- "**Focusing on the robotics cell output**": it emphasizes the high-quality output of the robotic system to optimize the productivity and efficiency of the robotic cell;
- "**Eliminate of waste**": this is one of the lean principles and lean manufacturing systems that is also applied in lean robotics systems to identify any activity or process that does not add value to the final service;
- "**Leverage the skills**": it emphasizes that robots should perform repetitive and dangerous tasks that align with their strengths and that humans can perform more creative tasks.

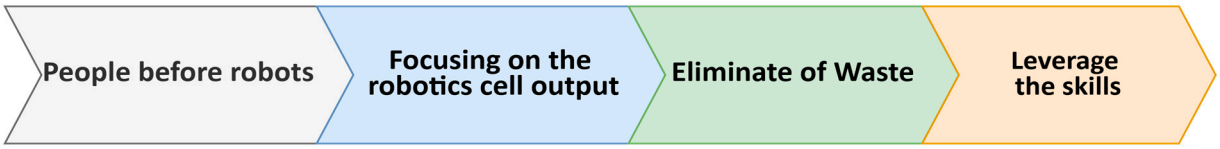


Figure 5. Core ideas from lean robotics and automation frameworks.

In manufacturing systems, several technological advancements in robotics systems have been shown as part of the development of the human–robot collaboration. The advancements focused on integrating robotics systems in terms of safety [25], the collaboration with humans in a shared workspace [26], in the context of HRC in automotive assembly to enhance safety and efficiency [27], and finally within the context of HRC in a production environment, focusing on continuous improvement and safety by optimizing HRC systems in the manufacturing sectors [28]. Figure 6: The use of robotics systems in the context of HRC summarizes the use of robotics systems in the context of HRC. It describes how each article adopted the use of robotics systems in the context of HRC by integrating cutting-edge technologies.

Exploring the use of HRC, given the multifaceted nature of the benefits of robotics systems, one might naturally assume that all companies utilizing automation technologies tend to perform well. This could be a result of the staggering amount of investment it demands.

Each article provides examples of how advanced technologies are applied to improve HRC, including sensor-based safety system, machine learning and AI algorithms, and flexible robotics systems.

Lean robotics systems with human–robot collaboration (HRC) emphasize the integration of robots into lean production environments, where robots and human workers can work together to optimize processes, increase productivity, and reduce waste. Thus, the lean robotics system with HRC can be represented as follows:

$$LRS_HRC = Min(W) + Max(P) + Opt(T)$$

where

- W = waste (time, material, or energy);
- P = productivity (output per unit of time);

- T = task optimized in HRC.

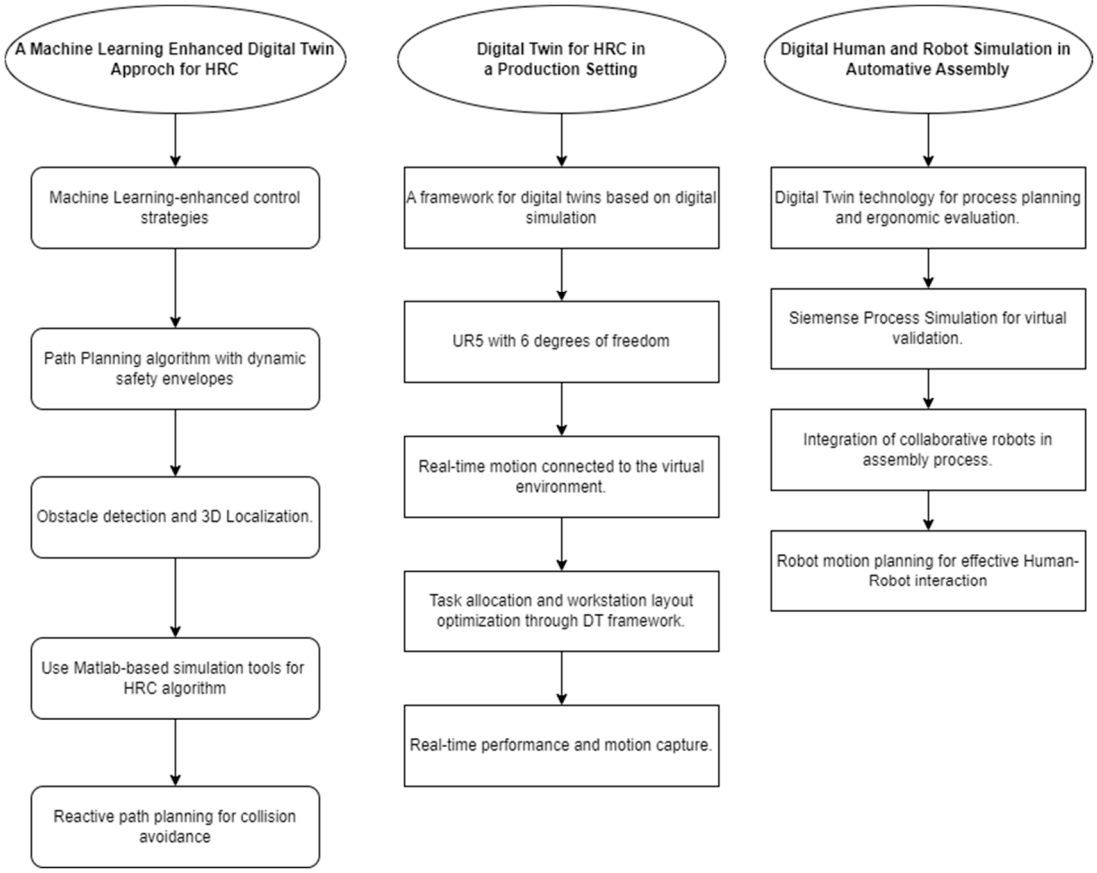


Figure 6. The use of robotics systems in the context of human-robot-collaboration.

This implementation faces several challenges, like precision and flexibility, and system integration to drive the human operator to work with the robot in a safe mode. Safety remains critical in the design and deployment of robotics systems to create a secure environment for both humans and robots. However, the key components of the model represent human collaboration which refers to designing robotic systems that are aware of human presence, robot task allocation, and interaction zones. Figure 7: The step-by-step path to achieving a robotic system with HRC illustrates the step-by-step path to achieving a robotic system with HRC, starting from identifying the suitable task for the HRC, followed by the technology selection, then the workforce integration through professional training. Digital twin is utilized for testing the performance.

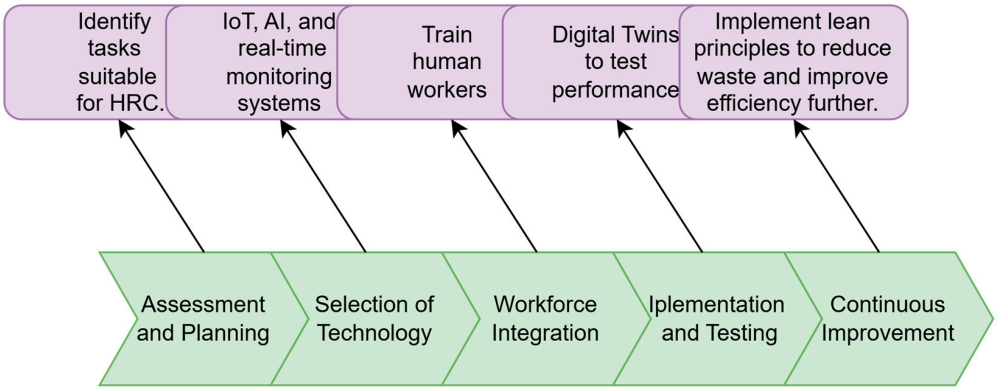


Figure 7. The step-by-step path to achieving a robotic system with HRC.

The highest level of lean robotics and HRC is known as the intelligent lean production environment, which refers to smart lean manufacturing. To achieve this level, some difficulties can be faced, for instance, human acceptance to work next to the robot, cost management, and safety regulations for human–robot interaction. At this level, productivity can be maximized, waste goes near zero, and safety is guaranteed.

However, for small local companies, the ability to boost product output through automation proves to be the most promising economically feasible investment paradigm today. For instance, one study has developed a robotic programming system in electronics manufacturing for small and medium-sized enterprises (SMEs) by combining ML with professional robot programming, interacting with human–machine interfaces (HMIs), and increasing the precision through vision systems and IoT [29]. Additionally, integrating advanced technologies like AI methods and reinforcement learning (RL) techniques within robotics systems offers new skills. RL supports complex motion planning along continuous trajectories while integrating RL within evolution strategies to learn robotic skills [30,31]. However, Table 3: The technological advancement and the utilized technology illustrates the technological advancement and the utilized technology.

Table 3. The technological advancement and the utilized technology.

Technological Advancements	Used Technologies
Reinforcement Learning (RL) for complex motion planning tasks in industrial robots [30]	Six-degrees-of-freedom robot (UR5 robot), visual sensor (camera), image processing, robot simulation.
Integration of reinforcement learning (RL) and evolution strategies (ESs) for robot skill learning [31].	Dynamic movement primitives (DMPs), policy improvement algorithms, evolution strategies (ESs).

It becomes clear that there has been substantial advancement in the development of intelligent systems when comparing the present and modern technologies with those utilized in robotics systems in the past. By collecting and analyzing data, modern robots can sense, act, and respond so that they operate more effectively within manufacturing processes. As a means of explanation, this integration of lean with robotics systems leads to many operational measures such as quality, cost efficiency, precision, less hazardousness, and flexibility. Authors considered that "the degree of automation in construction is far less than in other industries, such as manufacturing. This results in both poor productivity and risky working conditions. Automation and robotics applications are opportunities to solve such issues in construction industry" [32]. Many real-world robotics applications could change the manufacturing process to make it leaner, such as the following: 1. Food industrial applications—palletizing decreases the cycle time and the cost. Robots can speed up the palletizing process, reduce workplace injuries, and adapt to different products compared with manual handling. For instance, the lean robotics system in the frozen food processing industry can palletize products where it would be uncomfortable for human workers. (speed, less hazardous); 2. Vision robotics application—inspection can make the system much leaner, especially in operations where operators need to make a visual decision (inspections). These applications contribute to the lean objectives of quality control, waste reduction, and data-driven decision-making; 3. Assembly operations handle repetitive tasks with precision and speed, ensuring consistent quality and reducing the likelihood of errors; 4. A single robot performing multiple tasks increases the ability to create a leaner manufacturing system by improving efficiency and decreasing the cycle time; and 5. In material handling applications, robots can be game-changers.

Most manufacturers have adopted industrial robots to simplify and automate their production processes. However, to maintain, sustain, and enhance the capabilities of industrial robots, the future should also involve the integration of lean principles into either

the design of robotic systems or the production processes with robots [33–35]. Indeed, to achieve this, lean activities continuously include value stream mapping to eliminate waste and achieve the aim of continuous improvement [36,37]. Key indicators of lean robotics systems are presented in Table 4. In this sense, major synergies can be noted between lean principles and robotic workflow as a flexible framework to fit the unique needs of operations.

Table 4. Key indicators of lean robotics systems.

Flexible Automation	Robots are deployed in manufacturing systems to handle a variety of tasks, adapting to changes in production needs.
Human Robot Collaboration	Robots perform repetitive tasks and humans focus on more complex activity. Workers and robots can collaborate closely for better performance.
Error Reduction	Robots can precisely perform tasks and reduce defects and errors in production systems.
Decision-Making	Robots can be connected via IoT for real-time monitoring and data analysis, leading to better process optimization.

An objective should be established to make the profits of robotics even greater by removing waste with a lean robotics approach that will take advantage of the following strategy. At the production process level, the result of lean robotics is improving production processes in terms of reducing wasteful activities, thus increasing efficiency and system productivity, representing the functions of (F8) quickly adapt to changes and (F9) cost savings. So, in terms of a pure business perspective, the top area for cost savings in integrating robotic systems is increasing productivity through full utilization of production by 24/7 operation. In combination with the ability to operate in this situation, the same interaction also sees the ability to adapt to changes in lead times due to increased production output [38].

6. Voice of Use Table Function Deployment Analysis

Based on the scope of integrating lean principles into lean robotics systems, this study provides a framework for how to assess and enhance lean robotics systems by generating VoT and KPIs, offering critical insights and strategies to provide researchers, engineers, and industry professionals with the best practices and skills for integrating lean principles within robotics systems to enhance production processes in manufacturing systems to gain unparalleled and invaluable perspectives into the complex and intricate workings of lean robotics systems and efficiently optimize their performance. Thus, it goes without saying that this framework has the potential to revolutionize the field of lean robotics, reshape the landscape of industrial manufacturing environments, and indubitably propel the entire industry into a new era of unprecedented efficiency, optimized productivity, and unparalleled success [39,40]. The proposed approach can thus be used to assess the performance of different configuration types of robotics applications in the manufacturing environment. Subject: lean robotics, lean principles. Functions: (F1) decrease interruption, (F2) quality control, (F3) speed up production process, (F4) decrease waiting time, (F5) eliminate unnecessary motion, (F6) eliminate non-value added, (F7) product mix, (F8) quickly adapt to changes (F9) cost savings.

The main functions are shown in Table 5. Voice of use table performance function deployment.

Table 5. Voice of use table performance function deployment.

No	Function	Why	Criticality	Means to Achieve Them
F1	Decrease Interruption	enhance efficiency, waste reduction continuous improvement, and error prevention.	Critical	1. Ensure reliable communication within the robotic cell and implement real time alert systems. 2. Train operators on system application and troubleshooting procedures. 3. Establish a comprehensive maintenance plan based on equipment requirements and usage. 4. Utilize condition monitoring techniques for real time robot status analysis.
F2	Quality Control	Focus on error prevention, process optimization, and adaptability.	Critical	1. integrate sensors and advanced programming for data capture and communication. 2. Define communication protocols interfaces for human-robot interaction. 3. Program robots for predefined testcases and interactions.
F3	Speed up Production	Align with customer demand, waste reduction, and continuous improvement.	High	1. Optimize robot programming for efficiency and invest in advanced robotic technologies. 2. Minimize human intervention by automating processes. 3. implement parallel execution through multi-threaded programming.
F4	Decrease Waiting Time	Enhance cycle time, waste reduction, and flexibility.	High	Optimze equipment setup and configuaration. 2. Utilize real-time data processing for immediate feedback. 3. Leverage digital technologies for issues identification and resolution.
F5	Eliminate Unnecessary Motion	Focus on waste reduction, process optimzation, and resource efficiency.	Critical	1. implement automation to reduce manual handling. 2. Analyze robot path and trajectory for optimization. 3Optimize robot testing trajectories and sequences.
F6	Eliminate Non-Value Added	Enhance customer value, minimize waste, and optimize resources.	High	1. Apply lean principles like 7 Wastes for waste identification and elimination. 2. Conduct value-stream mapping for process analysis and improvement. 3. implement pull systems and error-proofing mechanisms
F7	Product Mix	Maximize production and enhance resilience.	Critical	1. Analyze market demand and align product mix accordingly. 2. Design adaptable setup interfaces for product variations. 3. identify and capitalize on opportunities for product mix efficiency improvements.

Table 5. *Cont.*

No	Function	Why	Criticality	Means to Achieve Them
F8	Quick Adapt to Changes	Focus on customer satisfaction, operational agility, and efficiency	High	1. Develop software for real time product and material availability assessment, 2. Adopt iterative execution processes for easy modifications. 3. implement configurable tests in robot programming for adaptability
F9	Cost Saving	Aim for faster ROl through error reduction and resource optimization	Critical	1. Focus on error-proofing mechanisms like sensors and validation checks. 2. Employ data analysis for insights into testing efficiency and defect rates, 3. Leverage automation for labor cost reduction and workflow optimization.

Table 6: Key performance indicators produced below were based on the functions from Table 5. Voice of use table performance function deployment and the investigation of lean concepts in lean robotics systems. The KPIs are important as they directly influence reliability, quality, and adaptability. Each of them was measured using a unique set of metrics, including millimeters for accuracy, counts or hours for interruptions, percentages for quality, lean adoption level, and flexibility measures to ensure performance evaluation and relevance. This also includes information on how to integrate robots in novel ways according to the size and complexity of the company. The proposal can be aligned with the processes of customer companies and can help to improve the process/product they deliver as a technical solution that points out some innovative methods that lean robotics automation should follow in their project and design.

Lean is implemented as a form of continuous improvement, involving both employee problem-solving and automatic system feedback to help improve the system over time [41,42]. Looking ahead, lean therefore involves more than just tools. It involves a culture shift of pursuing the best through sustained learning and growth [43,44].

It is increasingly evident that the complete robotic system needs to be considered and discussed between the experts in robotic technology, the end users, and the manufacturing teams. Below at Table 7. Relational matrix of the correlation and KPIs is the relational matrix in the proper matrix format, showing Functions (F1–F10) as rows, KPIs as columns, and their respective correlation percentages.

The insights demonstrated the need for engaging in direct and open conversation at an early stage of the development process, which is even more important while exposing the underlying capabilities required to engage with robotic systems. Functions such as F1 and F4 highlight the importance of optimizing maintenance requirements and minimizing interruptions, underlining the role of these KPIs in ensuring a seamless process. Quality remains at the center across multiple functions (F2, F5, F6, F8), underscoring its significance in lean robotics systems. Moreover, adaptability is represented by test flexibility and level of lean adaptation. Functions related to productivity and cost-savings (F3, F6, F7) (F3, F6, F10) are strongly linked by their correlations. These correlations lead to enhancing productivity, reflecting positively on cost savings. Across all functions, there is a pronounced correlation between functions' objectives and the KPIs. For instance, F2 focuses on accuracy and quality, emphasizing the alignment of objectives with performance metrics. Factors such as cost savings and product mix in a task-defined project are particularly important and

especially crucial to increasing efficiency that has longer-term positive outcomes [45,46]. This might include enhanced inter-team relationships across organizational units and more inclusive, longer-term technological solutions as our interest is in helping engineering professionals. Robotics serves as a complement to these lean principles by ensuring job uniformity, thus eliminating waste in the form of defects, rework, and inconvenience and operational costs, and ensuring better quality [47,48].

Table 6. Key performance indicators.

No	KPI List	KPI importance	Measuring System	Target
1	Productivity	Enhance operational efficiency and output.	Percentage (%)	>25%
2	Cost-Saving	Optimize resource utilization and reduce expenses.	Euro/Range	<15%
3	Cycle Time	Ensure swift execution and minimize delays.	Seconds per one execution	>range (3–10) s
4	Accuracy	Ensure precision in operations and results.	Millimeters (mm)	+/−0.01 mm
5	Quality Measure	Ensure high standards of output and customer satisfaction.	Percentage (%)	100%
6	Level of Lean Adaptation	Enhance operational efficiency and continuous improvement.	Percentage (%)	100%
7	Level of interruption	Minimize disruptions to ensure consistent production and maintain system reliability	Count Frequency	Target frequency
8	Error Reduction	Enhance product quality and reduce waste!	Number or Percentage (%)	Target reduction rate
9	Maintenance Requirements	Ensure equipment longevity and minimize downtime.	Hours of Operation	Non-Stop
10	Flexibility measure	Ensure system adaptability to changes and operational shifts	Percentage (%)	100%

Table 7. Relational matrix of the correlation and KPIs.

Functions/KPIs	Level of Interruption	Error Reduction	Maintenenace Requirements	Accuracy	Quality Measure	Defect Rate	Productivity	Cost Saving	Cycle Time	Change over Time	Throughput	Level of Lean Adaptation	Test Efficiency	Test Flexibility	Product Mix
F1	100	90	80	-	-	-	-	-	-	-	-	-	-	-	-
F2	-	-	-	90	100	80	-	-	-	-	-	-	-	-	-
F3	-	-	-	-	-	-	80	70	90	80	80	-	-	-	-
F4	90	-	-	-	-	-	-	-	-	90	-	-	-	-	-
F5	-	-	-	-	-80	-	-	-	-	-	-	90	80	90	-
F6	-	90	-	-	-80	-	90	90	-	-	-	80	-	-	-
F7	-	-	-	-	-	-	-	-	-	80	-	-	-	90	80
F8	-	-	-	-	-80	-	-	-	-	-	-	-	-	-	100
F9	-	-	-	-	-	-	-	-	-	-	-	90	-	100	-
F10	-	90	80	-	-	-	-	80	-		-	-	-	-	-

7. Results and Discussion

Organizations can strategically use the KPIs to track improvements and performance by integrating them into a plan followed by lean principles and lean robotics systems, as shown in Table 8: Track improvements and performance strategies. Utilizing lean technologies, such as value stream mapping, to track productivity levels of robotics systems with real-time monitoring tools, regularly analyze data to make improvements, invest in training, optimize methods, and put lean procedures into practice. Lean waste strategies, such as just-in-time inventory management, take advantage of cost-cutting measures that identify and eliminate waste in manufacturing processes for the next stage in the production and supply chain. Using precision robots puts quality control procedures into action, and it tracks the amount of time spent on each activity or procedure. Lean adaptation level empowers continuous improvement and incorporates lean ideas into everyday operations and culture, put robots in operation, provide error-proofing measures in place, and offers instructions to track errors and determine their underlying causes.

Table 8. Track improvements and performance strategies.

KPI	Plan Strategies	Implementation
Productivity	Implement lean processes, optimize techniques, invest in training programs, and upgrade technology	Apply lean tools like Value Stream mapping, use real-time monitoring tools to track productivity levels. Analyze data regularly for improvement.
Cost Saving	Identify and eliminate waste in processes and resources, eliminate bottlenecks, and automate repetitive tasks	Conduct lean waste techniques like Just-In-Time inventory management, compare actual expenses with budgets identify and implement cost-saving opportunities
Accuracy	Implement quality control measures, provide training, and use precision tools. Ensure precision through standardized processes and continues improvement.	Regularly update procedures for accuracy, apply lean quality control, and implement corrective actions for observed deviations.
Cycle time	Streamline processes using lean methodologies to reduce delays and bottlenecks.	Monitor the time taken for each task, or process, implement lean six sigma to analyze and improve process efficiency
Level of lean adaptation	Integrate lean principles into daily operations and culture, conduct lean training programs, and empower continuous improvement	Develop a roadmap for further lean integration and training and enhance lean practices
Error reduction	Implement error-proofing mechanisms, provide training, and conduct regular quality checks	Monitor errors and identify root causes. implement corrective actions to reduce errors
Flexibility measure	Fostering a lean culture and investing in versatile systems. Provide cross training for employees	Implement lean flexibility strategy like Single-Minute exchange of Die(SMED) for rapid changeover

The integration of robotic systems and lean principles could contribute to reducing lead time and increasing the flexibility and quality of the processes and the process-related

products. Moreover, if this specific focus on robotic systems is followed, the potential also lies in designing these systems to be able to cooperate and learn from the actual production process.

Robotics offers a significant contribution to the enhancement of the production process through the plan strategy, which has illustrated the use of lean principles in the implementation of a robotic solution to provide organizations with comprehensive benefits. The practical implications, in terms of the introduction of lean robotics and factors for the best practices for the long-term future of manufacturing systems, are significant. Although the underlying concepts focus on an established technology, it is proposed that the potential contribution goes beyond a visual conduction in current best practice. Overall, this proposal for the deployment of lean principles with robotics becomes central.

The use of robotic systems in various manufacturing industries is expanding [49]. At the same time, a lot of research focuses on improving the design and performance of these systems, thereby reducing their costs and improving their autonomy [50,51]. A potential approach for making production more efficient is the design and integration of lean principles into the control systems of these robots [52]. The purpose of this integration is to design a system that, apart from carrying out process-related tasks, also helps to reduce waste and therefore make production more efficient in terms of time, costs, and quality [53,54]. This is beneficial for organizations with high market demand, which are trying to reduce waste in their processes and trying to reduce, or even eliminate, human intervention in these processes. By integrating robotic system behaviors with lean principles, the organization's production process could be optimized to better suit market needs and to cover as many customer requirements as possible.

Figure 8: Structured guide of a roadmap for integrating lean principles into robotics systems is a structured guide of a roadmap for integrating lean principles into robotics systems that involves blending lean methodologies with advanced automation technologies. However, there is an urgent call for accelerating the deployment of lean principles within robotics systems. This important synergy combines the power of automation with methodologies to catch up with the continuous changes in the market. Manufacturers should be encouraged and supported to embrace meaningful changes, to adapt to this evolving landscape, and to develop new practices. The combined contribution of lean and robotics could form the seedbed for innovative lean research, showing the manufacturing community that novel manufacturing strategies are not only viable but can lead to attractive levels of sustainability and efficiency. Manufacturers incorporating lean can experience significant competitive advantage. The potential values of the combined capabilities from robotics and lean systems are expected to generate increasingly influential discoveries relevant to manufacturing practice and research. Lean-trained leaders must remain central to the process and to informing and educating the remaining workforce in lean practices. Enhancing efficiency, optimizing resource usage, improving safety, and achieving standardization are the goals of integrating lean principles into robotics systems. This integration is based on lean approaches, such as value, value stream, flow, pull, and perfection.

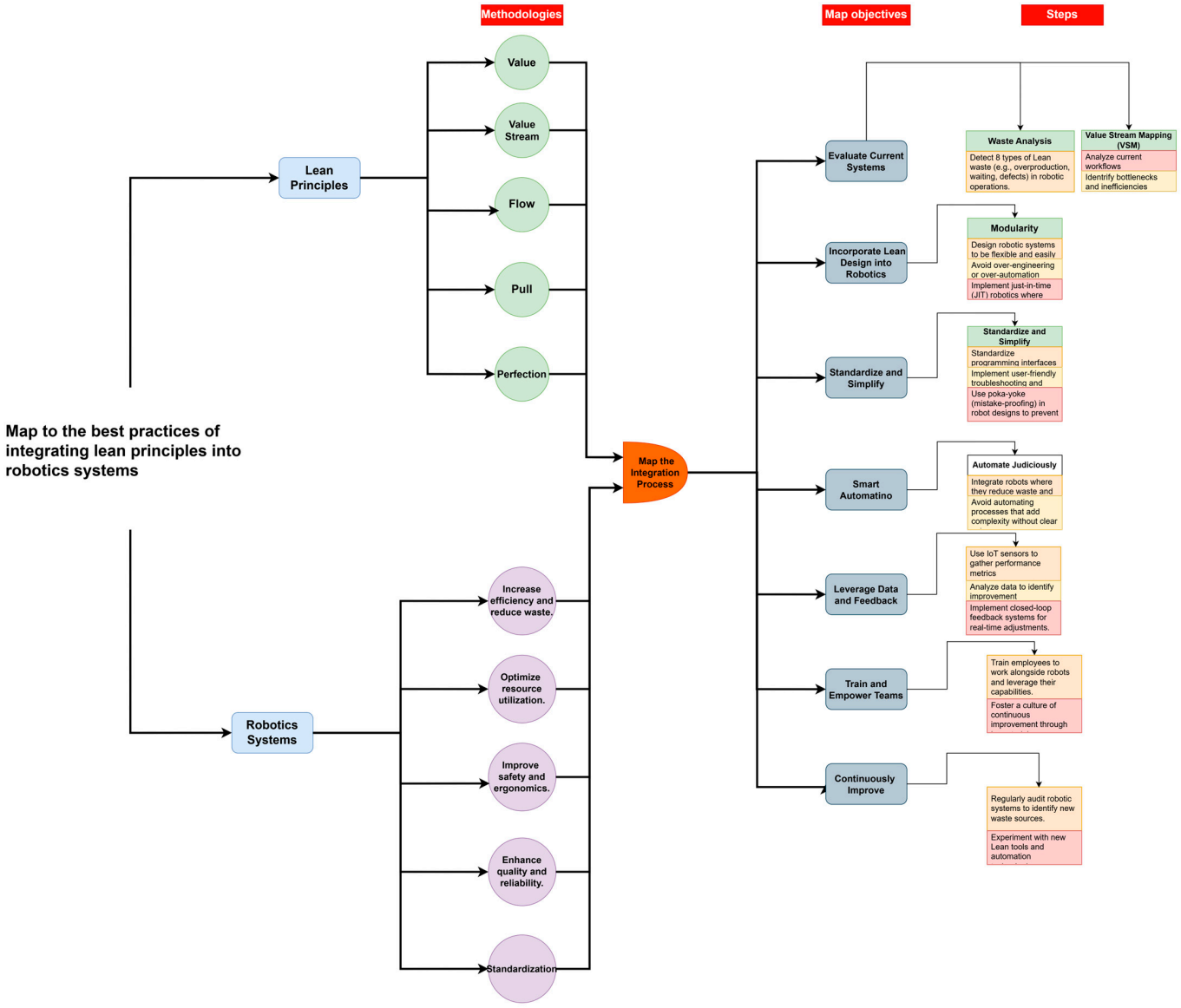


Figure 8. Structured guide of a roadmap for integrating lean principles into robotics systems.

8. Conclusions

The research serves as a comprehensive framework of lean principles applied in robotics systems for enhanced production processes. At the same time, lean robotics systems developed in accordance with lean methodologies will be able to flexibly respond to the evolving market demands and production schedules. The current phase of robotics systems is to concentrate on process optimization to adapt to the changes of the global markets.

In order to enhance production processes, teams must be empowered and trained, with a focus on fostering a culture of continuous improvement, standardization, and simplification to encourage problem-solving and teaching workers how to collaborate with robots. Last but not least, ongoing improvement is accomplished by testing out new lean tools and automation technologies as well as conducting routine audits of robotic systems to identify new waste sources. This methodology guarantees a smooth and effective fusion of lean concepts with robotics.

The primary focus of future research will go through evaluating the impact of lean robotics systems on agility and adaptability in modern manufacturing to investigate how robots can be dynamically adapted and responded to market demands by combining a case

study and simulation-based analysis through the deployment of robots in manufacturing environments by designing a construction 3D printing robotics system (C3DPRS) for modern houses under the concepts of lean principles to transform the traditional challenges of building, such as labor shortages and long project timelines to introducing more flexibility, efficiency, and modernize construction to streamline robot integration, reduce waste, and optimize the process of getting a robotic system running in production.

Examining human–robot collaboration in lean production environments is another crucial area of research to assist in exploring the effects of collaborative robotics systems and providing strategies for workforce empowerment and process optimization to particularly ensure that human workers are equipped, skilled, and prepared to work alongside these advanced systems and to investigate how the integration of lean robotics systems can streamline manufacturing processes and enhance overall operational efficiency. Nevertheless, it is necessary to design and implement scalable lean robotics systems for small and medium-sized enterprises (SMEs) by identifying and addressing potential obstacles in incorporating lean principles into robotics systems to create a comprehensive analysis of the current technical challenges through a case study of the Fold Station project, which uses the robot for destacking and gluing the stone papers for further processes, to provide and understand the role of lean robotics systems in SMEs, concentrating on agility, adaptability, human–robot collaboration, scalability, and process optimization.

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