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The Role of Additive Manufacturing in Advancing Lean Production System

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Abstract: Additive Manufacturing (AM), often referred to as 3D printing, is transforming the contemporary manufacturing environment through flexibility enhancement, waste identification and reduction, as well as rapid prototyping enablement. The integration of AM into Lean Production System (LPS) has the potential to improve quality and production efficiency, enhance throughput and profitability, and also minimize resource consumption. This paper systematically explores the synergy between AM and LPS which leads to not just waste reduction, but increases customization and also fosters Just-In-Time (JIT) Manufacturing. It also offers a detailed review of their impact on production processes, sustainability, and scalability. Furthermore, the paper discussed the limitations of AM and provided future directions in adopting AM within lean frameworks, and also emphasized on Industry 4.0 technologies.

Keywords: additive manufacturing, lean production system, sustainability, industry 4.0, waste reduction, just-in-time

I. Introduction

To make effective decisions, companies that are integrating Additive Manufacturing (AM) and Lean Manufacturing (LM) strategies must understand their synergies. This integration can enhance productivity, customer satisfaction, operational efficiency, and sustainability goals. (Lakshmanan et al., 2023). Lean Production System is a strategic production approach aimed at minimizing waste, it helps industries to maximize service resources, optimize production, and enhance customer satisfaction (Okpala et al., 2020; Ihueze and Okpala, 2014). This idea originated in Japan after World War II, when Japanese manufacturers realized that they could not afford the enormous costs required to rebuild ravaged facilities (Okpala, 2013b). Similarly, the aim of Lean Manufacturing (LM) is a production system that reduces wastes, optimize the creation of values for customers, and also utilizes fewer resources to manufacture high quality products at less the time, thereby increasing throughput and profitability (Okpala, 2014; Ihueze and Okpala, 2011).

Modern manufacturing demands enhanced flexibility and personalization of products, but this demand cannot be achieved effectively without incurring large amounts of waste using the traditional manufacturing methods. These factors pose a significant challenge to manufacturing industries which led them to search for new tools and techniques to address the demands of the 21st-century manufacturing, without jeopardizing product quality and customers' satisfaction at a low cost. The process of Lean production is depicted in Figure 1.

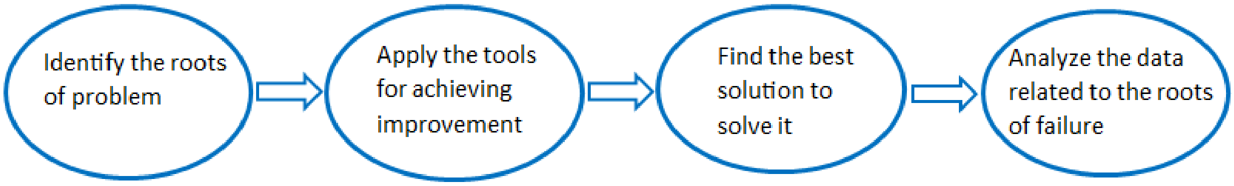

Figure 1: Process of lean production. Source: Abhishek Dixit et al. (2015)

Additive Manufacturing, commonly referred to as 3D printing, is revolutionizing production systems. It enables greater customization and the production of on-demand components, thereby optimizing lead times and reducing the need for large inventories (Alabi, 2024). The 3D digital model is typically created with the application of Computer Aided Design (CAD), but reverse engineering methods such as 3D laser scanning or MRI/CT techniques may be applied to produce existing part geometry digitally. Here, the solid model will be converted into an acceptable format appropriate for AM processing (Strong et al., 2018). ASTM International defines AM technology based on seven principles as shown in Table 1, these principles can be implemented using several key technologies, materials, and applications (Rahito et al., 2019).

Table 1: Principles of Additive Manufacturing. Source: Rahito et al. (2019).

ASTM Category	Basic Principles	Example of AM Technology
Material Extrusion (ME)	The precipitation of build material occurs when droplets are released through a heated nozzle.	3D inkjet technology Fused Deposition Modeling (FDM)

Binder Jetting (BJ)	Liquid printing binder is applied layer by layer to specific coordinates, binding the material fragments together to form a 3D object.	3D inkjet technology
Vat Photo Polymerization (VP)	Light curing is applied to the liquid polymer in a vat.	Digital Light Processing (DLP), Stereo Lithography
Powder Bed Fusion (PBF)	The use of focused thermal energy to fuse an exact point in a small area of the build material's powder bed.	Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Laser Sintering/Melting (SLS/SLM)
Direct Energy Deposition (DED)	The application of powder material occurs simultaneously with the application of focused thermal energy, which melts the material at the target location.	Electron Beam,Laser Engineered Net Shaping (LENS), Plasma Arc Melting Laser cladding (LC)
Sheet Lamination (SE)	Attachment of sheets or foils of materials.	Ultrasound consolidation/ Ultrasound Additive Manufacturing (UC/UAM), Laminated Object Manufacturing (LOM)
Cold Spray	Adhesion drives the high-velocity propulsion of injected powder to form material.	Multi-Metal Deposition

AM has expanded its applications into many fields, including medical, electronics, fashion, automotive, construction, and research (Wimpenny et al., 2016). It evolved from a rapid prototyping tool to a manufacturing technology capable of producing effective end-user products (Parupelli and Desai, 2019). Polymers, metals, ceramics, electronic materials, and biological materials can all be additively processed (Gibson et al., 2021), as well as lightweight products (Oettmeier and Hofmann, 2017). However, the most commonly used materials are thermoplastics, ceramic pastes, metal, and ceramic powder and metal. (Guo and Leu, 2013).

Additive Manufacturing: A Tool for Lean Production

Additive Manufacturing is transforming traditional production systems by aligning with the principles of Lean Manufacturing. As depicted in figure 2, it complements lean principles by reducing waste, minimizing inventory, and improving production flexibility.

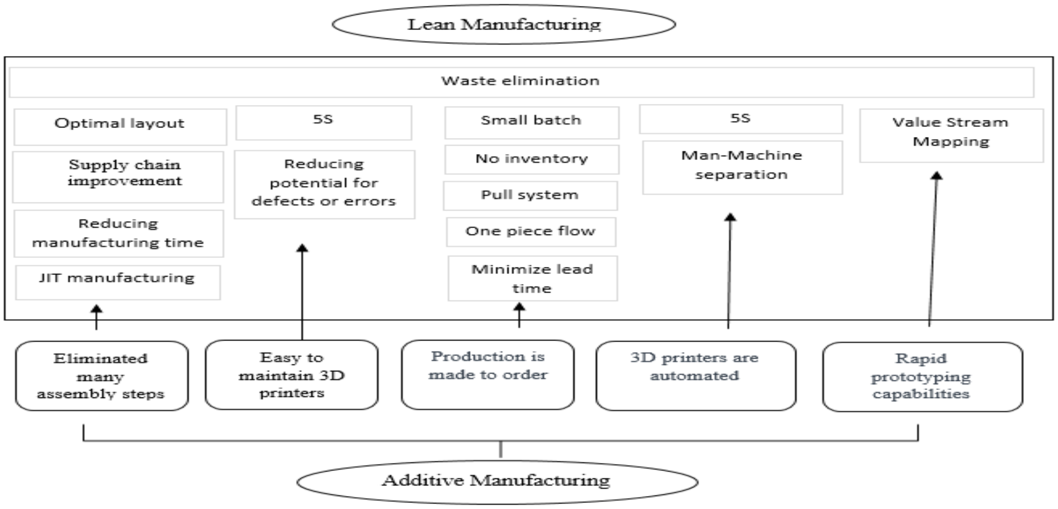

Figure 2: Contribution of AM in achieving lean production system objectives. Source: Driouach et al. (2023).

Table 2 highlights real-world examples and comparative case studies on the role of additive manufacturing in advancing lean production system.

Table 2: Case Studies

Company	Industry	Additive Manufacturing Application	Impact on Lean Production	Key Takeaways
General Electric (GE)	Aerospace	3D-printed fuel nozzles for jet engines	Reduced part count from 20 to 1, 25% weight reduction, and lower	Improved efficiency, cost savings, and sustainability

			material waste	
BMW	Automotive	3D-printed jigs, fixtures, and spare parts	Faster prototyping, reduced lead time by 80%	Increased flexibility, cost reduction, and leaner workflows
Siemens	Energy	3D-printed gas turbine blades	Increased efficiency, improved part performance, and reduced production time	Enhances lean manufacturing through rapid iteration and lower waste
Adidas	Consumer Goods	3D-printed midsoles (Futurecraft 4D)	Shortened supply chain, reduced inventory needs	On-demand production, customization, and waste minimization
Boeing	Aerospace	Additive manufacturing for lightweight parts	Weight reduction, lower fuel consumption, reduced production complexity	Supports lean by minimizing overproduction and enhancing efficiency
Ford	Automotive	3D-printed prototypes and tools	90% cost reduction in tooling and increased speed to market	Eliminates excess inventory and accelerates development cycles
John Deere	Agriculture	On-demand 3D printing of spare parts	Reduced downtime and minimized excess stock	Leaner inventory management and improved serviceability
NASA	Space Technology	3D printing of spacecraft components	Lightweight structures, cost savings, and in-space manufacturing	Enables lean and agile production for space exploration

Waste Reduction

The 21st-century product design cannot be achieved effectively without incurring large amounts of waste with the traditional manufacturing methods, as displayed in Table 3. These trends and patterns are emerging as a result of technological, economic, and social progress (Ferreira et al., 2020). Therefore, modified processes are required to create a clean environment.

Table 3: Material Efficiency in Subtractive vs. Additive Manufacturing. Source: Gibson et al. (2021)

Process	Material Usage (%)	Waste Generated (%)
Additive	90–95	5–10
Subtractive	50–60	40–50

Additive Manufacturing (AM) is an important technological enhancer necessary for the implementation of a circular economy. This is because the circular economy enables the regeneration of material flows while also striking a balance between economic development and resource sustainability. AM is expected to use less material than 3D printing, produce less waste, and be recyclable (Huang et al., 2020). It also allows for complex geometries that are often unattainable with traditional techniques because of its layer-by-layer approach (Gibson et al., 2015), and is a reuse method to recycle thermoplastic and resource optimization (Kreiger et al., 2013; Santander et al., 2020).

Time and Cost Reduction

Traditional lean production system rely heavily on Just-In-Time (JIT) production to reduce wastes and inventory costs (Okpala, 2013a). The seven inherent wastes in manufacturing processes which lean manufacturing identifies, reduces, or possibly eliminates are depicted in figure 3.

Figure 3: The seven inherent wastes in manufacturing processes. Source: Okpala (2014)

According to Sasson and Johnson, (2016), production costs can be divided into two categories: The first category contains well-structured costs like materials, labor and machine costs. The second category contains unstructured costs, like those associated with build breakdown, machine setup, and inventory. However, some of the most significant advantages and cost minimization in additive manufacturing may be concealed in poorly structured costs. Because additive manufacturing can potentially create a complete unit in one build, it reduces the need for some inventory and transportation costs, which has an impact throughout the supply chain (Thomas, 2016). AM further enhances JIT by enabling on-demand production, where components are manufactured when required, thereby eliminate the necessity of large inventories and also reduce lead times.

Enhanced Design Capabilities

AM introduces unparalleled design flexibility, which aligns closely with LPS principles of continuous improvement and responsiveness to customer demands. It provides distinctive technical and economic advantages, like the ability to fabricate intricate geometry, compatibility with generative design techniques, and the opportunity for low-cost fabrication of relatively few parts (Gibson et al., 2021; Leary et al., 2021). This capability allows manufacturing companies to consolidate multiple parts into a single design, thus reducing assembly time and improving product reliability, which is impossible or inefficient with traditional methods.

Sustainability and Energy Efficiency

The sustainability benefits of AM align with lean production’s principle of resource optimization. AM systems often use recyclable materials, and their energy consumption can be lower than traditional systems when producing small batches. Furthermore, localized production enabled by AM reduces transportation needs, which tends to reduce carbon emissions. (Baumers et al., 2011). AM also supports sustainable manufacturing by reducing material usage during the design iteration process, and ensures that only the required material is used, thus minimizing waste even during experimentation with multiple design iterations.

Agile Design Iterations

In traditional manufacturing, altering a product’s design can require extensive retooling, resulting in increased costs and production delays. The integration of AM into LPS eliminates these barriers by allowing for rapid design iteration through digital modeling. Nike company applies AM to produce customized shoe soles that are tailored to individual athletes' foot structures and performance needs. The rapid prototyping enabled by AM reduced development time by over 30%, thus enabling Nike to respond to customer feedback and market trends effectively (Hou, 2023). Adidas also uses AM in its Futurecraft line to create shoes with mid-soles customized to an individual’s running style and biomechanics. Manufacturers can quickly prototype, test and refine components without disrupting the production line. This innovation has resulted in increased customer engagement and higher product demand.

Adaptation to Market Changes and Customization

AM facilitates a lean and responsive manufacturing approach by enabling rapid adjustments in production in response to customer feedback or market demands. It also empowers manufacturers to deliver mass-customized products that meet specific customer requirements, without the added complexity of traditional methods. The medical device industry has used AM to create custom implants, hearing aids, and prosthetics. For example, 98% of global hearing devices are now produced using AM, allowing a perfect fit for patients while minimizing lead times and costs (Wohlers, 2021).

Improved Quality and Reliability

Improved quality and reliability are central tenets of lean manufacturing. Modern AM systems include integrated sensors and monitoring tools that provide real-time feedback on production quality. The process of designing with reliability in mind involves understanding and incorporating the fundamental variations introduced in a process (Leemis, 2009). Statistical design methods allow for the inclusion of statistical distributions for prevalent design values to inform engineering decisions based on variability in mechanical, geometric, and operating parameters. (Tuegel and Penmetsa, 2006).

The precision, consistency, and customization offered by AM ensure that components meet strict quality standards, especially in high-stakes industries like aerospace and medical devices. Boeing for instance, uses AM to manufacture titanium parts for its 787 Dreamliner, thus enabling them to achieve dimensional accuracy within micrometers, which is essential for aerodynamics and safety standards (Boeing, 2020). In the automotive industry, AM is used to create precision parts for engines and other critical systems. Ford (2018), observed that the reduction in defects has improved reliability and longevity, with manufacturers reporting up to a 25% decrease in warranty claims due to improved part quality.

II. Challenges in Implementation

Implementing additive manufacturing systems within lean manufacturing presents several challenges, despite the potential benefits of enhanced efficiency and reduced waste. The integration of these technologies requires careful consideration of various barriers that can hinder successful adoption. Table 4 highlights the benefits and challenges of applying Additive Manufacturing (AM) in advancing Lean Production System.

Table 4: Benefits and challenges of AM application on LPS

Aspect	Benefits of Additive Manufacturing (AM) in Lean Production	Challenges of Additive Manufacturing (AM) in Lean Production
Waste Reduction	Minimizes material waste by using only the required material.	High initial material costs and material availability issues.
Customization	Enables on-demand, customer-specific production.	Longer design-to-production time for complex parts.
Inventory Management	Reduces the need for large inventories through on-demand manufacturing.	Requires robust digital infrastructure for efficient operation.
Lead Time Reduction	Speeds up prototyping and production, reducing cycle time.	Slower printing speeds for large-scale production.
Complexity in Design	Facilitates complex and lightweight designs without extra costs.	Requires skilled workforce for design optimization.
Supply Chain Efficiency	Shortens supply chains by enabling localized production.	Dependence on consistent raw material supply and standards.
Energy Efficiency	Uses less energy compared to traditional subtractive methods.	Some AM processes have high energy consumption per unit.
Tooling Cost Reduction	Eliminates the need for expensive molds and tools.	Limited material options for end-use functional parts.
Sustainability	Supports sustainability goals by using recyclable materials.	Some AM materials are not biodegradable or widely recyclable.
Scalability	Ideal for low to medium-volume production with flexibility.	Less competitive for mass production compared to traditional methods.

Industries are leveraging hybrid approaches, AI-driven optimizations, and automation to address AM challenges. These strategies enhance cost-efficiency, speed, material performance, and sustainability, making AM a key enabler of Lean Production Systems. Table 5 depicts how industries are overcoming the challenges of **Additive Manufacturing (AM) in Advancing Lean Production Systems** with specific strategies.

Table 5: Surmounting the challenges of AM in advancing LPS

Challenge	Industry Example	Strategy Used	Impact on Lean Production
High Initial Investment & Material Costs	**GE Aviation**	**Hybrid Manufacturing** (combining AM with traditional machining)	Reduces costs, improves efficiency, and maintains precision
Slow Production Speed & Scalability Issues	**Siemens**	**AI-Based Process Optimization** (AI-driven print path optimization)	Enhances speed, minimizes waste, and improves scalability
Material Limitations & Quality Control	**NASA & Boeing**	**Advanced Material Development & In-Situ Monitoring**	Ensures consistent product quality and expands material choices
Post-Processing Complexity	**BMW**	**Automated Post-Processing & Surface Finishing**	Reduces lead time, improves efficiency, and eliminates manual inefficiencies
Integration into Existing Supply Chains	**John Deere & Ford**	**Distributed & On-Demand Manufacturing**	Lowers inventory costs and supports Just-in-Time (JIT) manufacturing
Skilled Workforce Gap	**Siemens & HP**	**AI & Automation for Simplified Operations**	Reduces the need for expert operators and improves workforce efficiency
Environmental Concerns (Energy Usage & Waste Management)	**Adidas Futurecraft 4D**	**Sustainable Manufacturing & Circular Economy**	Reduces waste, promotes sustainability, and aligns with lean principles

High Initial Investment

One of the most significant challenges to the wide spread use of additive manufacturing lies in its high initial investment costs. To successfully integrate AM into lean manufacturing requires substantial capital for the acquisition of equipment and training for specialized knowledge. Sharma et al. (2024), explained that smaller manufacturers or organizations with limited budgets often find it difficult to adopt AM. It is advised that smaller organizations should source for collaborative financing, outsource AM services, or lease. AM implementayion in an SME differs from that of a large global organization, this is because investing in new manufacturing technologies is frequently associated with the market structure and organizational size. The size of a manufacturing facility is a crucial factor in implementing new technology successfully, thus before adopting a new manufacturing technology, an organization may need to redesign its systems and procedures (Saberi et al., 2010).

Material Limitations

One of the primary limitations of additive manufacturing is the limited number of materials that can be used concurrently. This limitation can impact the performance, durability, and quality of the final products. According to Zuo et al. (2024), traditional AM techniques often rely on single-material processes, thereby limiting the functionality and application of printed parts, particularly in large-scale applications, but Tang et al. (2023), suggested that advances in Scalable Multiple-Material Additive Manufacturing (SMAM) can address these limitations by integrating various materials and enhancing process control.

The range of printable materials in AM is restricted, particularly for high-temperature applications. Also, insufficient data on the mechanical properties of available materials further complicates material selection, thus affecting the overall effectiveness of designs (Marzola et al., 2020). Consequently, this restriction on choice of material can limit the broader adoption of additive manufacturing for certain applications, which is common where diverse material properties are essential for the product’s functionality and lifespan. The variety and properties of materials available for AM applications are still evolving but are not as extensive as those available through conventional methods. As a result, companies looking to adopt AM must carefully assess the specific material requirements of their production needs and determine whether AM can meet those needs effectively.

Scalability for High-Volume Products

Several factors affect the scalability of additive manufacturing processes for high-volume production in lean manufacturing, including: technological innovation, operational management practices, and process stability. AM is particularly well suited for low to medium production volumes, rapid prototyping, and custom manufacturing. Innovations in AM technologies can significantly improve process parameters such as time, cost, and dependability, this enables AM to compete with traditional manufacturing methods (Huang et al., 2021). Scalable multiple-material additive manufacturing systems enhance production capabilities by integrating features like in-line quality inspection and error correction, which are essential for maintaining high standards in mass production (Qu et al., 2022). To effectively improve the volume of mass production, there should be a significant increase in the printers used. This approach allows for the parallel production of multiple parts or the same part across different machines. However, Mellor et al. (2014), posited that the synchronization and continuous monitoring of print jobs across machines can be managed with software.

The Future of AM in Lean Production System

The future of Additive Manufacturing within Lean Production System is set to undergo significant evolution, driven by the incorporation of digital technologies and the principles of Industry 4.0. Table 6 outlines the future prospects of Additive Manufacturing (AM) in Lean Production Systems.

Table 6: Future prospects and potential impact of AM on LPS

Future Prospect	Potential Impact on Lean Production System
Advanced Materials	Development of stronger, lightweight, and sustainable materials will enhance production efficiency and product performance.
Faster Printing Speeds	Improved AM technologies will significantly reduce production time, making lean manufacturing more agile.
Mass Customization	AM will enable large-scale personalization of products without increasing production costs.
Integrated AI & Automation	AI-driven design optimization and automated AM processes will enhance precision and reduce human intervention.
On-Demand Manufacturing	Distributed manufacturing models will minimize supply chain dependencies and reduce inventory waste.
Hybrid Manufacturing	Combining AM with traditional methods (e.g., CNC machining) will optimize production for complex and high-strength components.
Sustainability Innovations	Use of biodegradable and recycled materials will align AM with eco-friendly lean practices.
Scalability Improvements	Advances in multi-material and high-speed 3D printing will make AM more viable for mass production.
Enhanced Digital Twin	Digital replicas of manufacturing processes will improve real-time monitoring and predictive

Technology	maintenance.
Regulatory & Standardization Developments	Improved industry standards and regulations will increase reliability and wider adoption in lean production.

Hybrid Systems in Lean Manufacturing.

The hybrid of the lean management system is a combination of some elements from lean technology to be integrated into two or three elements, which offer the opportunity to leverage the strengths of both technologies. The integration of simulation tools with lean value stream mapping enables manufacturers to visualize and optimize production scenarios dynamically (Abdel-Jaber et al., 2022). This system will help to organize a better workplace for efficiency and reduce waste (Ahmad et al., 2017). Successful implementation of these processes can improve communication between processes, reducing waiting times from 14% to 11% and achieve optimal line balancing (Ani et al., 2022). Also it can effectively reduce non-value-added activities, leading to improved overall equipment effectiveness Pimpalkar and Madgule, (2024). Bevilacqua et al., (2015), narrated that the incorporation of lean practices with AM results to lead time reduction, reduction of batch change and transition intervals by up to 50%, while increasing the overall efficiency of equipment by 25%. These systems enable manufacturers to meet production demands more effectively while adhering to lean principles. Hybridizing additive manufacturing with lean manufacturing methods also provides a way to overcome additive manufacturing's limitations in large-scale manufacturing conditions.

Integration with Industry 4.0

The combination of additive manufacturing and Industry 4.0 represents an unprecedented change in manufacturing processes, increasing efficiency, customization, and sustainability. This synergy uses advanced technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin Technology to optimize supply chain management and production. Industry 4.0 systems apply AI for the analysis of data for the prediction and management of process errors, (MELTER et al., 2024) and supports real-time monitoring and data analytics, which allows for immediate adjustments in AM processes (Sousa et al., 2024). AM plays a crucial role in smart factories, where interconnected systems enhance operational efficiency and reduce downtime (Jafar et al., 2024).

The use of IoT devices and data analytics improves operational efficiency, allowing manufacturers to respond quickly to market demands and customer preferences with the application of sensors (Khorasani et al., 2022; Igbokwe et al., 2024a). These sensors provide real-time tracking of the printing process, achieving over 98% accuracy in spatial localization, which is crucial for defect identification (Akhavan et al., 2024). Manufacturing companies can optimize production schedules and reduce time to market by simulating manufacturing processes in real time with the application of digital twin technology.

Some of the challenges with the integration of industry 4.0 include initial investment and the necessary infrastructure (Nwankwo et al., 2024; Igbokwe et al.,2024b), the lack of compatible technologies, such as advanced robotics and AI (Arteaga and Chan, 2021; Okpala and Okpala, 2024), and a lack of skilled personnel. Addressing these issues is critical for full realization of the potential of AM in a competitive manufacturing environment.

III. Conclusion

Additive manufacturing has demonstrated considerable potential as a valuable tool in Lean Production System through the provision of solutions to key lean principles. One of its most compelling features is the ability to minimize material waste with the usage of the exact amount of material required for each component, unlike traditional subtractive manufacturing methods. It also enhances on-demand production, and also reduces overproduction and excess inventory wastes. Successful implementation of these processes leads to lower energy consumption and reduced carbon footprints, thus aligning with sustainable manufacturing goals. This contributes not only to cost savings but also supports sustainability initiatives within production systems.

However, despite its obvious benefits, AM faces a number of challenges that may impede its widespread adoption. While there are challenges that could be addressed, the potential of additive manufacturing to drive continuous improvement in production processes is undeniable. As the technology matures and is integrated with other advanced manufacturing techniques, AM will play a more significant role in the future of lean manufacturing. As it will enable manufacturers to meet the growing demands for customization, sustainability, and efficiency, ultimately empowering companies to deliver greater value to their customers.

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