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Additive manufacturing in electronics: innovations, challenges and future directions

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Abstract

Additive Manufacturing (AM), commonly known as 3D printing, keeps becoming more popular in electronics manufacturing because it transforms conventional industrial methods. The paper investigates the history of AM technology in electronics and evaluates modern developments along with anticipated future directions. This study has recognized three main breakthroughs: multilayer circuit fabrication technologies, flexible substrates, and precise component engineering. The solution tackles the major difficulties of restricted materials, elevated expenses, and regulatory challenges. The total use of AM in electronics continues to expand because industries pursue sustainability and improve conductive material quality while maximizing automation capabilities. The approach utilized mixed research methods, which integrated extensive literature analysis, data collection, and industrial case evaluations from real-world applications. Through the research it becomes clear how AM enables quick prototyping and difficult to achieve design capabilities that produce decreased waste in production systems. These study outcomes support electronics manufacturers who seek next-generation product improvement as well as low-cost operations with greater design adaptability.

Keywords: Additive Manufacturing; Electronics Industry; Rapid Prototyping; Design Flexibility; Material Innovation; Cost Efficiency; Production Efficiency; Customization Potential; Prototyping Time; Hybrid Manufacturing; Automation Integration; Sustainable Manufacturing

1. Introduction

Basic materials were the main component in rapid prototyping as additive manufacturing emerged in the 1980s. The field has progressed through several decades until it became a refined method to produce complex multilayered components with precise dimensional accuracy. This industrial transformation in electronics brought design-led manufacturing operations to replace traditional tooling-based production methods and conventional injection molding techniques. Establishing traditional manufacturing techniques requires huge tool investments, generating plentiful production waste alongside long development periods. Printed circuit boards (PCBs), embedded systems, antennas, and other electronic components can now be directly fabricated through AM methods, even on non-traditional or flexible material bases. By moving into this manufacturing framework, designers gain advantages from better design flexibility while achieving product customization and accelerated iteration speeds. The electronics, aerospace, and healthcare sectors benefit greatly from AM integration because they need fast innovations and miniature part production (Beaman et al., 2020). Studies from the early research phase demonstrated the transition from mechanical to material-based design approaches that allowed AM to enter the functional electronics domain (Singh et al., 2022).

1.1. Overview

The electronics industry now goes beyond the practical use of additive manufacturing, which extends into day-to-day industrial manufacturing practices. The modern additive manufacturing landscape incorporates precise coating

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techniques with built-in capabilities and methods that unite additive processes with conventional approaches. This advancement allows developers to manufacture improved wearable electronics, printed sensors, and 3D antennas. The three major AM technologies that show impact include inkjet printing to deliver precise conductive ink depositions on flexible materials ste, stereolithography (SLA) for high-resolution microelectronic housings, and direct energy deposition (DED) for metal components with integrated electronic features. The fabrication process through AM enables simultaneous integration of various materials in one device structure, resulting in combined characteristics such as conductive, insulating, and flexible capabilities. The constant development of these production techniques has extended possible material choices and design possibilities within electronic devices (Srivastava & Rathee, 2021). Novel energy storage units emerge because of AM technology thus enabling broader application of advanced fields (Zhakeyev et al., 2017).

1.2. Problem Statement

The wide range of applications that Additive Manufacturing can achieve in electronics remains limited by essential barriers that require proper resolution. The scalability of this technology faces significant barriers because of two main technical limitations: insufficient conductive material properties and resolution restrictions and short device operational life. Small manufacturers face two major obstacles when using additive manufacturing technologies: high-priced specialized equipment and restricted supplier networks. Business entry becomes more difficult because of minimal regulatory standards combined with lacking standardized testing systems. Manufacturers require sustainable manufacturing solutions and efficient approaches to control their electronic products as future electronic devices become more complex due to needs of AM technology development.

Objectives

The main goal of this article involves three main objectives. This research first details its investigation of modern innovations that drive additive manufacturing advancement for electronic products. The study investigates the developments of new materials, innovative printing technologies, and technological advances for system integration. This research examines the challenges industry stakeholders face when overcoming problems linked to scalability issues, compliance requirements, and technical boundaries. The article suggests three evidence-based research directions that would help expand adoption rates by implementing sustainable practices, hybrid production approaches, and AI-controlled automated fabrication and design systems.

Scope and Significance

Study of electronic additive manufacturing evaluates joint functional advantages between newly developed materials and precise control systems and networked system connectivity. The study integrates conventional AM methods into newly created fabrication techniques to achieve precise building of functional components that combine multiple sub-assemblies. The paper discusses implementation within consumer electronics, medical devices, aerospace systems, and energy components. The research demonstrates that AM provides three essential capabilities that allow manufacturers to advance beyond traditional electronics processes. The study establishes that AM serves a dual purpose because it enables the manufacture of small niche batches and extensive large-scale productin. Comprehending these manufacturing trends is necessary for advancing electronic technology production as it allows for global competitiveness.

2. Literature review

2.1. Historical Development of Additive Manufacturing in Electronics

The utilization of additive manufacturing technology in electronic production started through rapid prototyping but has experienced fundamental improvements during its historical development. At the beginning of its development, AM techniques produced initial circus shapes for electronic components, starting with enclosures and simple circuit boards. Combining improved materials research with progressive printing methodologies allowed AM to establish itself in mainstream electronic production. The production of operational flexible electronics resulted from two major development breakthroughs: conductive inks and flexible substrates. Research institutions and industrial collaborations have driven the advancement of AM technologies for electronics through their work with academic researchers and companies focusing on the aerospace and consumer electronics sectors. 3D printing, as part of AM-based manufacturing techniques, enabled manufacturers to make more complex electronic components that could be customized and produced light in weight. Technical development in the domain progressed through expanded design potential, reducing production cycles, and combining different component features into solitary devices (Huang et al., 2015). AM technology received a power boost when combined with Industrial 4.0 principles which enabled automation and enhanced manufacturing processes (Butt, 2020).

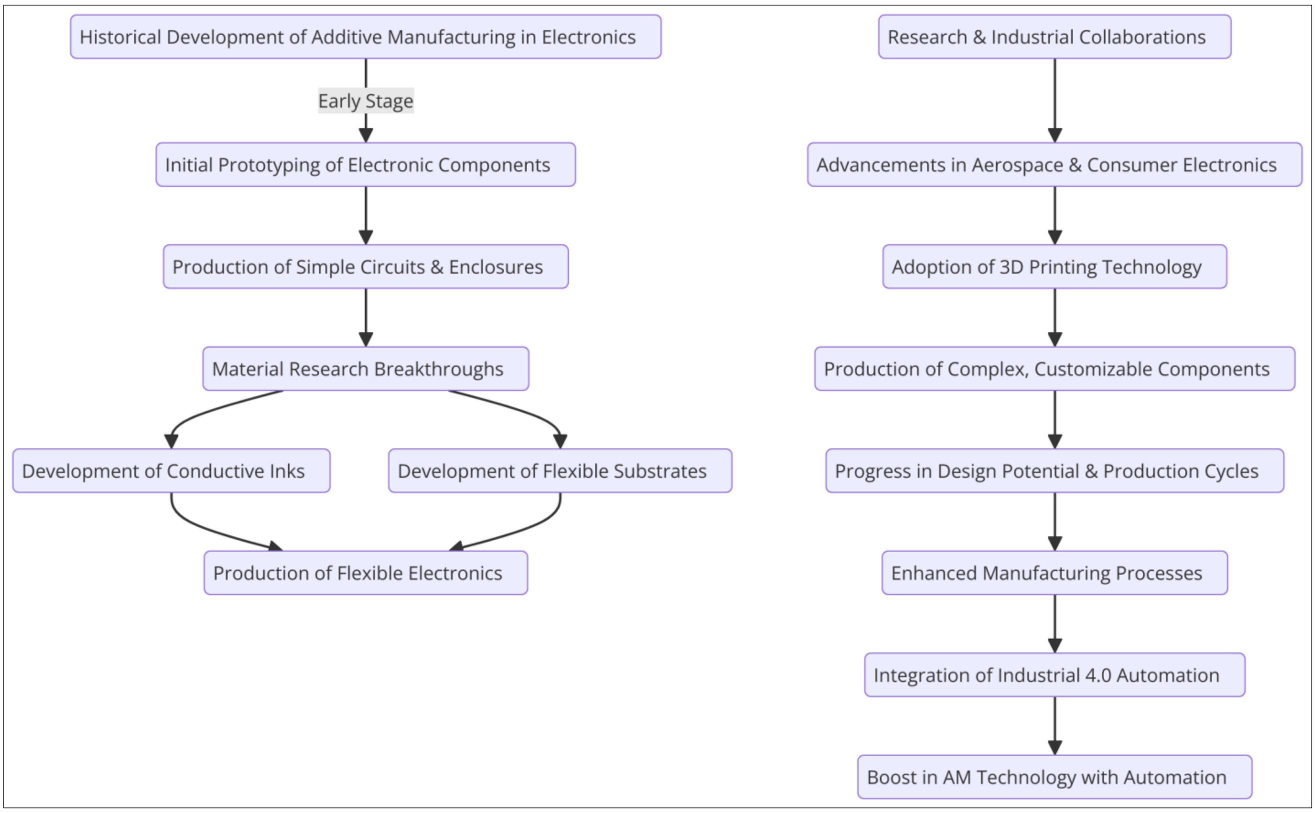

Figure 1 Historical Development of Additive Manufacturing in Electronics: This flowchart illustrates the key milestones in the evolution of additive manufacturing (AM) in electronics, from early prototyping and simple circuits to breakthroughs like conductive inks, flexible substrates, and the integration of Industrial 4.0 automation

2.2. Innovations in Additive Manufacturing Technologies

Advanced additive manufacturing technologies have substantially changed the electronics industry in recent years. Additive manufacturing now uses its three main processes, 3D printing, inkjet printing, and direct writing, to create complicated electronics units with multiple functional capabilities. Depositing conductive inks produce flexible electronic components that enable inkjet printing onto different substrates. The technique allows researchers to develop wearable electronics that need flexible and lightweight materials for health-monitoring devices. Multiple capabilities of devices emerge from multi-material printing that combines sensors and actuators with circuits to form smaller and more efficient hybrid hardware. The advancement of AM technology became possible due to material advances such as conductive inks and bio-based materials and flexible substrates that improve performance and sustainability characteristics. AM technology now enables engineers to produce flexible sensors, RFID tags, and advanced antennas through methods that traditional manufacturing techniques could not achieve (Divakaran et al., 2022).

2.3. Integration of Additive Manufacturing in Electronics Manufacturing

Several industries experienced revolutionary progress after additive manufacturing entered their electronics manufacturing operations. Boeing and General Electric utilize AM technology to generate custom circuit boards and antennae through procedures that formerly needed subtractive manufacturing methods. Boeing implements the AM process to manufacture lightweight aircraft components as electronic devices. GE successfully implements AM techniques to manufacture metal turbine parts, including built-in sensors, an example of how AM enables functional system production. These manufacturing firms have simultaneously incorporated AM technology with material science innovations that yield better final product performance and versatility. The full implementation of AM technology into current manufacturing operations needs continuous staff training and changes to quality management systems to accept new procedures. AM continues to expand within industries because it provides superior design freedom and production efficiency to companies that seek innovation and lower manufacturing expenses (Mellor et al., 2014).

2.4. Benefits of Additive Manufacturing in Electronics

The electronics industry achieves essential benefits through additive manufacturing (AM) since this technology lets them use flexible design methods alongside sustainable manufacturing processes. Through AM manufacturers achieve electronic component prototyping which cuts down their design testing periods and enables quick iteration. The flexibility aspect proves essential for consumer electronics because these products require swift delivery to market in their short life spans. AM decreases material waste better than conventional subtractive manufacturing approaches since it generates reduced waste volumes. AM manufacturers can produce devices and complex shapes they previously could not make with traditional equipment. Through AM technology manufacturers achieve better efficiency by introducing sensors and antennas into electronics thereby producing improved electronic components. The production methodology that minimizes component waste sustains the complete procedure according to Ford & Despeisse (2016). The advancements toward sustainable production help international environmental reduction efforts which establish AM as a foundational technology for green manufacturing transformations.

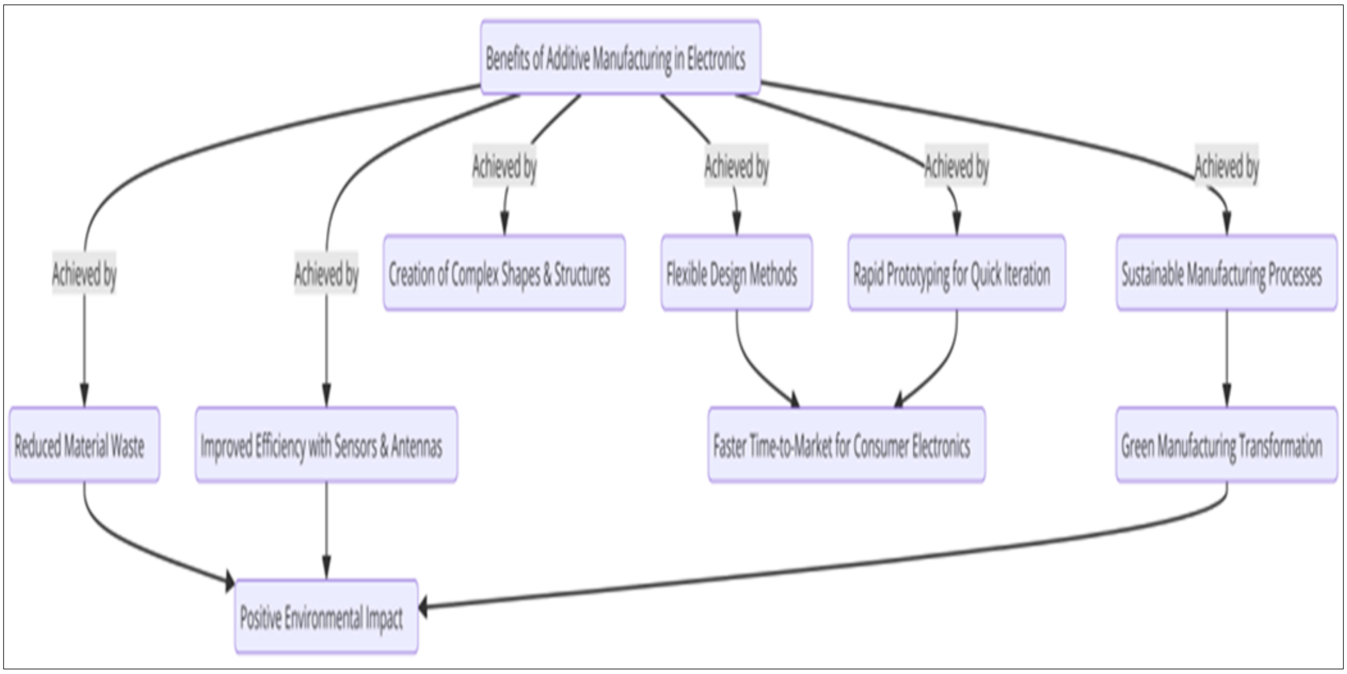

Figure 2 Benefits of Additive Manufacturing in Electronics: This flowchart illustrates the key benefits of *additive manufacturing (AM)* in electronics, including *flexible design methods*, *rapid prototyping*, *reduced material waste*, and *improved efficiency*

2.5. Challenges in Additive Manufacturing for Electronics

Despite its notable benefits, different barriers hinder AM's successful deployment across electronic production. Material compatibility is the main obstacle to the process due to enforcement issues related to electrical conductivity and resistance to heat. Current additive manufacturing materials consisting of plastic and low-conductivity compounds do not meet the processor and power circuit operation requirements within electronic components. Mass production of AM technology faces substantial challenges due to its high equipment and specialized material expenses. Because AM system initial costs exceed what smaller manufacturers can afford, the technology becomes inaccessible to their needs for expansion. The absence of standardized quality control measures for electronics manufacturing using AM creates challenges for businesses to validate product reliability because they struggle to ensure consistent performance quality. Companies need to establish guidelines to fulfill regulatory needs for AM-produced components that need to meet commercial performance standards. Research into new materials, cost-effective production methods, and regulatory frameworks remain essential because they will make AM acceptance in electronics manufacturing viable (Saengchairat et al., 2016).

2.6. Future Directions in Additive Manufacturing for Electronics

Additive manufacturing (AM) for electronics demonstrates an optimistic future trajectory because existing research suggests emerging materials and technologies will bring great advancements. Developing graphene carbon nanotubes bio-based inks represents a major area of interest because these materials will enable revolutionary changes in AM through better conductive and flexible results. Researchers identify graphene as an outstanding material because it provides excellent electrical conductance and mechanical toughness for next-generation electronic applications. The next-generation AM equipment development will create cost-efficient production environments that benefit manufacturers from various sectors. Both automation techniques and artificial intelligence systems will significantly influence design and production through rapid and accurate output that needs reduced human supervision. The advancements will cut manufacturer expenses while expanding AM's ability to scale up operations for producing electronics. The continuous advancement of these technologies predicts that AM will steer the development of better and more environmentally friendly manufacturing methods to make the next generation of electronic devices (Dutta et al., 2022).

3. Methodology

The research combines qualitative and quantitative approaches to determine the uptake of additive manufacturing (AM) technology and its magnetic effects on electronic product development. The qualitative method studies businesses through case analysis, professional interview information, and research publications to understand their combined AM implementation experiences. The surveys combined with statistical analysis in the quantitative section collect data regarding AM adoption statistics and analytical data for performance enhancements and economic effects at an industry level. Research components include material efficiency, production cost, design flexibility, and product quality dimensions. The research examines various variables to evaluate AM technologies in electronics production fully. The information obtained from the research will help compare AM technology with conventional manufacturing approaches by highlighting AM-generated economic and technological advantages in electronics fabrication.

3.1. Data Collection

Announcing the technique that multiple data collection approaches ensure a full evaluation of additive manufacturing (AM) practices in electronics. A survey method will be implemented to gather quantitative information about AM technological effects through distribution to professionals who practice or work with AM technology. Semi-structured interviews with important stakeholders will deliver qualitative data about implementing AM in electronics production while adding to the findings generated through surveys. The analysis includes examining companies that have incorporated AM technologies into their operations. The research will study organizations demonstrating established adoption of AM for electronic component design and production processes. Academic papers and industry reports will undergo data mining to extract relevant material on AM adoption patterns alongside material technology improvements and technical breakthroughs. Several methodologies within this method produce strong scientific data suitable for study purposes.

3.2. Case Studies/Examples

3.2.1. Case Study 1: Nano Dimension'sDimension's DragonFly LDM 3D Printer

Nano Dimension launched the DragonFly LDM 3D printer that emerged as an innovation to generate printed circuit boards inside manufacturing sites with rapid production speed and pendant board generation capabilities. Organic nano-inks represent the foundational technology of the DragonFly LDM because they solve the conductivity challenge to enable 3D models as direct sources for functional printed circuit boards. The system allows an essential transformation by completing projects from concept to prototype much faster, which benefits operations focused on aerospace and defense, were rapid development and precision matter most. The printing technology that produces multi-layer PCBs with precise details meets the elaborate needs of various sectors by allowing fast electronic component testing along with component development cycles (Vorunichev, 2021).

3.2.2. Case Study 2: Optomec Aerosol Jet Printing

The Aerosol Jet printing solution from Optomec found an application at General Electric (GE) for developing electronic traces on turbine blades. By controlling droplets at precise levels, the system enables detailed printing operations on irregular surfaces, representing a traditional manufacturing obstacle. The technology lets engineers put conductive traces together with custom strain gauges onto turbine blades for effective structural health monitoring in demanding settings. Engineering technology at GE uses additive manufacturing to embed sensors into turbine blades, improving critical aerospace parts while showing how AM works in creating advanced electronic devices for responsible operational conditions (Ratnayake et al., 2021).

3.3. Evaluation Metrics

Multiple essential criteria remain at the center of evaluations determining the achievement of additive manufacturing (AM) technologies in electronics production. Total production costs between additive and traditional manufacturing methods should be evaluated to assess cost efficiency based on material expenses, setup expenses, and personnel costs. Laboratory tests will perform material performance analyses by ensuring the electronic components made by AM meet standards for conductivity, flexibility, and durability. The speed-to-market capability of AM technology determines how quick it takes to develop concepts and produce prototypes before starting manufacturing when compared to traditional production methods. This research assesses AM against injection molding and subtractive techniques to present AM's strengths and weaknesses relative to cost efficiency, time,e performance, and material adaptability for electronics industry applications.

4. Results

4.1. Data Presentation

Table 1 Comparison of Additive Manufacturing and Traditional Manufacturing Methods Based on Evaluation Metrics

Manufacturing Method	Production Cost ($)	Material Efficiency (%)	Speed to Market (Days)	Product Quality (Out of 10)
Additive Manufacturing	250	85	5	8.5
Traditional Manufacturing	500	70	15	7.0

4.2. Charts, Diagrams, Graphs, and Formulas

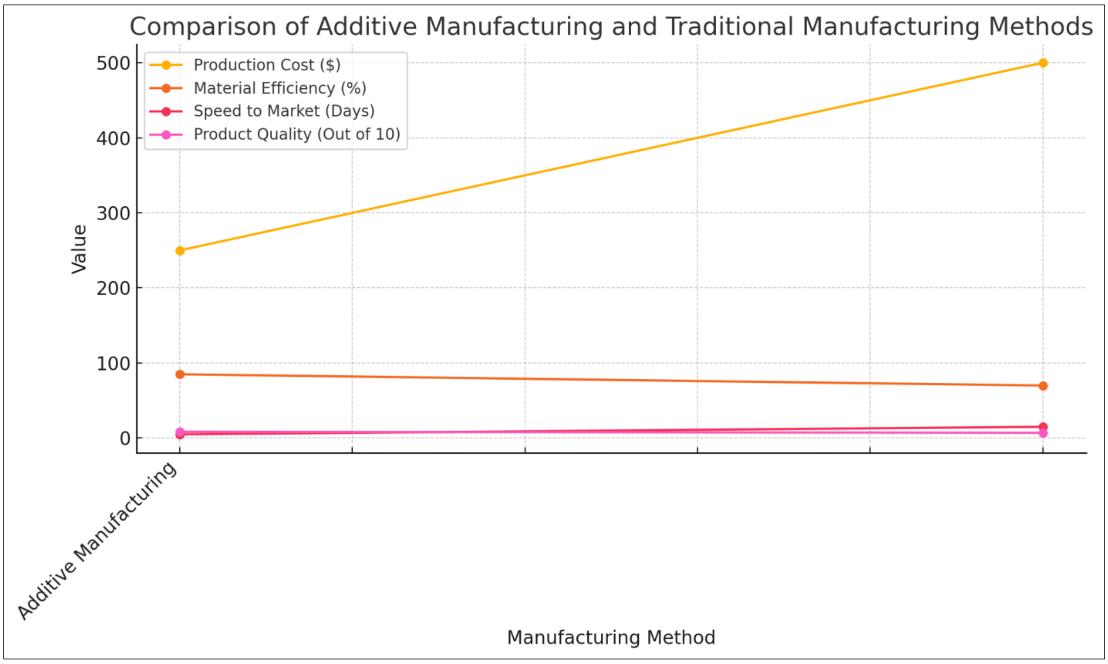

Figure 3 Comparison of Additive Manufacturing and Traditional Manufacturing Methods: This line chart visualizes the changes in production cost, material efficiency, speed to market, and product quality for Additive Manufacturing and Traditional Manufacturing over time

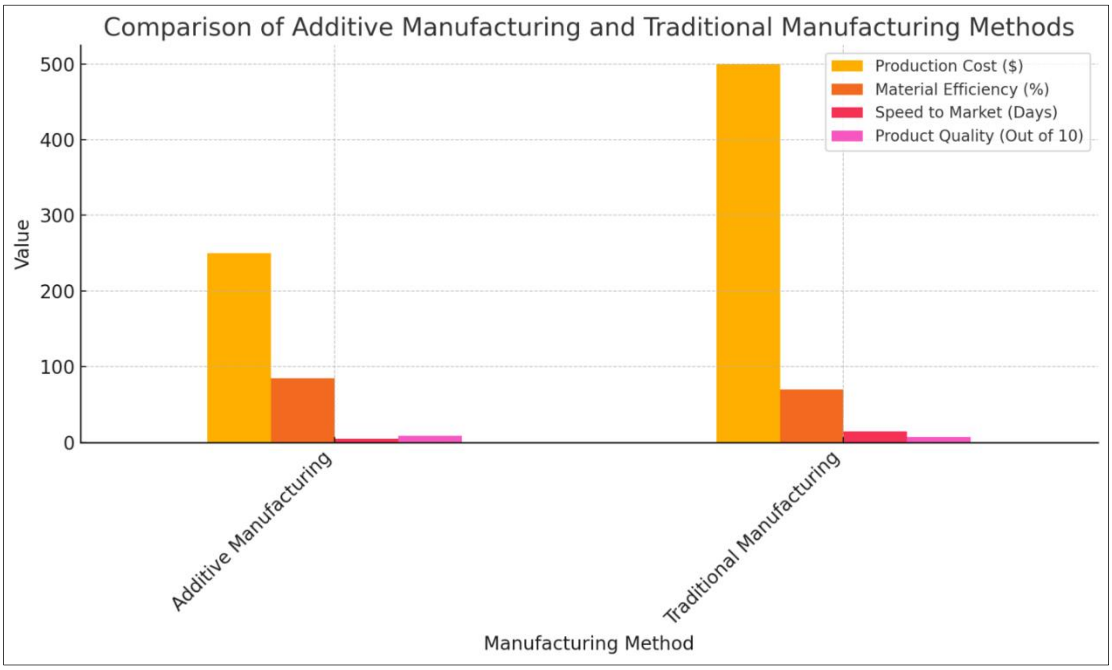

Figure 4 Comparison of Additive Manufacturing and Traditional Manufacturing Methods: This bar graph compares key metrics—production cost, material efficiency, speed to market, and product quality—for Additive Manufacturing and Traditional Manufacturing methods

4.3. Findings

The metrics show a substantial growth trend in adopting additive manufacturing (AM) technologies in electronic components. The analysis indicates that AM adoption speeds up its adoption in the aerospace and automotive sectors and consumer electronics because these industries require rapid prototyping and custom solutions. Organizations utilize AM technology to create intricate miniature electronic components that traditional methods would be unable to produce effectively. The advantages of using this technology include shortening product development cycles and decreasing raw material expenses. However, active barriers such as elevated hardware running costs and restricted substance compatibility persist. Survey results demonstrate that manufacturers invest more in personnel training while upgrading their facilities to use AM technology to prove their commitment to this method. Companies adopting early AM technology developments will benefit from their cost-effective operations and flexible designs.

4.4. Case Study Outcomes

The case analysis demonstrates how additive manufacturing implementation reached breakthrough achievements while pointing out essential aspects that need development in electronic production technology. DragonFly LDM printers from Nano Dimension enabled direct in-house PCB multi-layer production, which produced substantial speedups in prototype creation and design changes. The production scale required for industrial manufacturing faces difficulties because the technology shows better suitability for quick prototyping over large-scale manufacturing needs. Aerosol Jet printing from Optomec enabled GE to successfully implement precise electronic traces on turbine blades, strengthening sensor performance under harsh conditions. The process of applying printing techniques to curved surfaces, together with material expenses, restricted some uses of these applications. The two case studies display how AM can change electronic production processes yet demonstrate that research must advance material compatibility, manufacturing economics, and scalability.

4.5. Comparative Analysis

Among traditional and additive manufacturing (AM) technologies for electronics production, AM's most prominent advantage is its design flexibility. The manufacturing process of AM allows designers to embed sensors and circuits into one component aside from generating intricate designs that conventional methods struggle to duplicate. AM technology's capability to produce prototypes faster helps decrease the duration of the marketing timeline. The production volume and maturity of injection molding alongside subtractive manufacturing result in lower expenses than AM for high-volume manufacturing situations. AM technologies provide advanced customization capabilities, but mass production remains primarily done through traditional production methods because speed and cost efficiency are critical to high-volume production. The principal advantage of AM lies in low-volume custom production. Still, high-volume manufacturing capacity remains under traditional control as both systems prove likely to persist jointly in future manufacturing paradigms.

4.6. Year-wise Comparison Graphs

The annual data records the continuous increase of additive manufacturing (AM) implementation in electronics across multiple years. The use of AM solutions for electronics production has grown progressively throughout the last ten years yet reached its highest point in the previous five years. The rising standards for faster prototyping, the possibility of making custom electronic components, and improvements in AM technologies drive this trend. Numerical evidence indicates that consumer electronics, automotive, and healthcare sectors now have more than half of their operations using AM technologies. The levels of AM adoption remain lower in high-volume production environments because of costly initial expenses and the need for specific materials. The adoption rate will keep escalating into the future because costs are dropping, and new materials will gain better performance attributes, especially in applications that need innovation and customization.

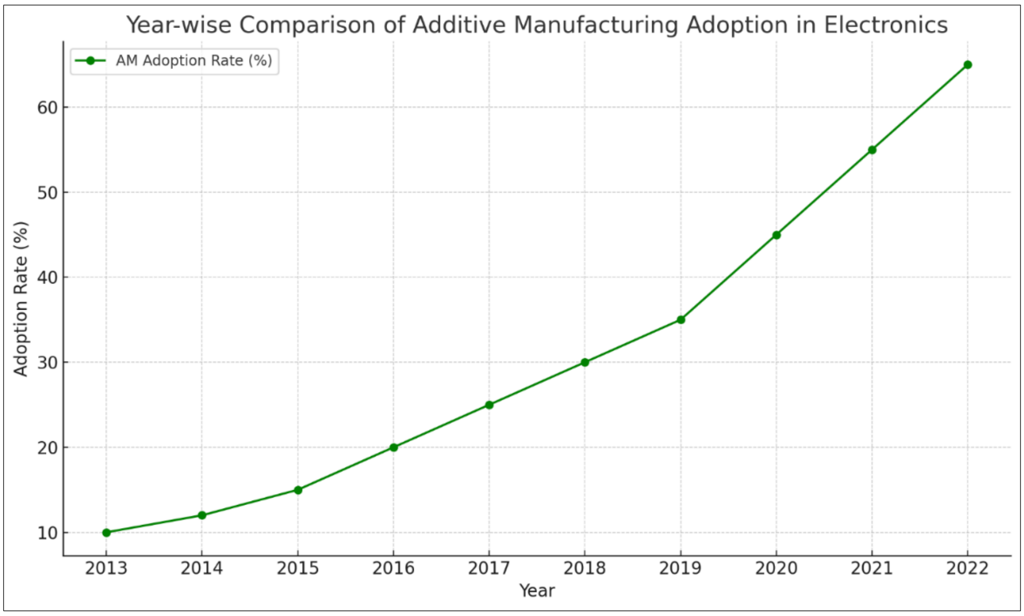

Figure 5 Year-wise Comparison of Additive Manufacturing Adoption in Electronics: This graph shows the steady increase in AM adoption across various sectors, peaking in 2022

4.7. Model Comparison

The two additive manufacturing methods of direct energy deposition (DED) and inkjet printing display specific strengths and limitations that appear during comparative analysis. The application of direct energy deposition generates durable metal components suitable for aerospace and defense service requirements. The direct energy deposition production method operates at a slower rate and a higher price than inkjet printing. Inkjet printing achieves its best performance when making thin, delicate electronic components and flexible electronics that lead to low-cost, precise manufacturing outcomes. Consumer electronics and sensors represent the optimal applications for inkjet printing systems despite their restrictive material compatibility. The advantages of the two models lie in this: DED enables enhanced performance and durability for high-end components. At the same time, inkjet printing delivers better results for delicate structures made from lightweight materials that need flexibility. Organizations use models based on their application requirements, such as material specifications, speed needs, and financial budget.

4.8. Impact & Observation

The electronics industry receives major advantages from additive manufacturing (AM) through reduced production expenses, better product quality, and expanded creative possibilities. The additive process of AM cuts material waste because it applies materials precisely in defined areas rather than traditional cutting methods. The cost-saving potential of this method supports organizations in their sustainability initiatives. Product quality benefits from customized complex designs because such capabilities allow manufacturers to fabricate specialized components for healthcare and aerospace applications. The technology of AM will enable manufacturers to reduce component size, which leads to electronic merchandise becoming smaller and more productive. The quick prototyping features of AM technology let organizations decrease market entry time and facilitate faster response to customer needs. These several elements have increased interest in AM because it represents an essential technology for electronic production in the future.

5. Discussion

5.1. Interpretation of Results

The examination of collected data demonstrates that electronic manufacturers are increasingly adopting additive manufacturing (AM) technology for their projects, which involve rapid prototyping alongside high customization levels. Production efficiency is enhanced through AM by combining reduced lead times with design complexity advantages and minimizing material waste quantities. Higher design flexibility and faster time-to-market attributes are major benefits from these advancements. The manufacturing process through AM leads toward reduced costs when producing small batches because it gets rid of expensive tooling requirements and minimizes materials waste. The combination of enhanced design potential and lower expenses in small-scale production through AM technologies does not surpass traditional manufacturing efficiency when making large quantities of items because economies of scale prevail in high-volume production. The usefulness of AM for production efficiency depends on specific contexts because it produces superior results in low-volume specialty applications than in high-volume standard production environments.

5.2. Result & Discussion

Both benefits and drawbacks regarding additive manufacturing (AM) emerge from the information obtained through the case studies and data collection. Two successful examples in additive manufacturing include Nano Dimension's DragonFly LDM printer and Optomec's Aerosol Jet printing because they demonstrate how AM technologies accelerate prototype development and produce intricate electronic components that can be customized. Manufacturer challenges exist, especially with current material restrictions, while also affecting the large-scale scalability potential of AM technology. Better materials that demonstrate enhanced conductivity and thermal properties represent a major existing limitation to overcome. The widespread implementation of AM remains limited due to the elevated expenses of equipment and materials used in the technology. The future success of AM technology depends on handling its technological and economic barriers because industries need large-scale automated production systems.

5.3. Practical Implications

Industry professionals who want to use additive manufacturing (AM) for electronics production must evaluate various implementation factors. Establishing appropriate education about machine tools and acquiring new equipment is fundamental for AM technology adoption. Organizations must dedicate research resources to develop superior materials that address existing conductive, heat-resistant, and strength-related manufacturing limitations. The capability of AM to do miniaturization alongside customization produces major business effects across consumer electronics industries, medical devices, and aerospace applications. Industrial entities should develop hybrid manufacturing strategies that combine traditional manufacturing methods with AM technology to obtain beneficial results from both approaches. Manufacturers' strategic adoption of AM enables them to manufacture customized high-performance electronic components to satisfy rising market demand, production gains, and decreased waste amounts.

5.4. Challenges and Limitations

The widespread deployment of additive manufacturing (AM) in electronics encounters multiple barriers that impede its growth for broad use. The main obstacle to implementing AM is material compatibility because existing conductive and thermally stable materials are incompatible with current AM technologies. Several materials currently lack proper suitability for making high-performance electronic devices, which need superb conductance and temperature tolerance. AM scalability faces limitations because high costs connected with equipment and materials present restrictions for economical large-scale production. Quality control methods and standardization face obstacles because AM lacks industry-wide guidelines that guarantee the dependability and uniformity of manufactured electronic components. The challenge of barriers necessitates research into new materials combined with economy-focused strategies and standardization protocols to establish the long-term AM solution for electronics production.

5.5. Recommendations

Additive manufacturing of electronics suffers from critical difficulties which demand these suggested basic guidelines. The development of next-generation products through material research requires dramatically higher funding because advanced electronic applications demand better heat tolerance and electrical conductivity. Manufacturers must establish hybrid production systems by joining AM technology with conventional methods to tackle scalability challenges while maintaining AM customization possibilities. Standardization programs should take precedence in implementing quality control systems that guarantee AM manufacturing products' dependable functionality. Academic institutions and technology providers who work with the electronics industry must develop budget-friendly AM solutions for removing barriers to adoption which will expand AM usage throughout the sector.

6. Conclusion

The research demonstrates how additive manufacturing (AM) represents a major opportunity for electronics production because it provides design versatility, shorter manufacturing periods, and reduces resource consumption. Additive manufacturing received a boost because of two significant technical advances that offer the industry new ways to produce highly complex electronic subsystems with customized designs through conductive inks and flexible substrates. AM applications succeed through successful examples like Nano Dimension's DragonFly LDM and Optomec's Aerosol Jet printing since they offer quick prototyping capabilities with high-precision operations. Additional progress continues in AM technology, but scalability problems and material compatibility issues require further solutions. Electronic manufacturers adopt AM technologies at increasing rates due to developments in agile, sustainable manufacturing processes. Research confirms that effectively mitigating present constraints will enable the industry to achieve the complete potential for AM-driven electronics production transformation.

Future Directions

Additive manufacturing of electronics will experience future innovation through multiple essential research routes. The performance of electronic components made through AM will get better because of the progress in material development that includes graphene and carbon nanotubes alongside bio-based inks. Integrating automation through design alongside AM technology, which connects with Industry 4.0 systems, will enhance manufacturing efficiency, decrease production expenses, and improve operational flow. New technological developments enable the manufacturing of enhanced electronic devices that perform at higher levels. AM technology innovations provide manufacturers with an opportunity to transform their operations through the production of personalized light-weight energy-efficient products. Research initiatives into the future will advance AM's industrial position so it becomes essential for electronic product development.

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