WORLD COMET RESEARCH GROUP

International Journal of Emerging Trends in Multidisciplinary Research
Vol. 5, No. 2, 2022
Doi: 10.67228/30715636/IJETMR-2022PII0B6P
PP. 01-13

Original Article

The Impact of 3D Printing Technologies on Modern Manufacturing

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Received: 11-07-2022 Revised: 11-26-2022 Accepted: 12-01-2022 Published: 12-03-2022

ABSTRACT

Additive Manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology in modern manufacturing. Unlike traditional subtractive methods, AM builds components layer by layer using computer-aided designs, reducing material waste and enabling the production of complex geometries and customized products. Over the past three decades, AM has evolved from a prototyping tool to a full-scale production technology used in industries such as aerospace, automotive, healthcare, construction, and consumer goods. Technologies including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Stereolithography (SLA), and Direct Metal Laser Sintering (DMLS) have expanded the range of printable materials such as polymers, metals, ceramics, and composites. This study analyzes the technological advancements, economic impact, and operational benefits of AM, focusing on factors such as cost efficiency, production time, material utilization, and supply chain resilience. The findings show that additive manufacturing significantly improves customization, reduces lead time, and minimizes material waste. However, challenges such as scalability, standardization, and cost in mass production remain. The study concludes that AM will play a key role in hybrid manufacturing systems to enhance industrial innovation and sustainability.

KEYWORDS

Additive Manufacturing, 3D Printing, Industry 4.0, Digital Manufacturing, Rapid Prototyping, Supply Chain Optimization, Sustainable Manufacturing, Mass Customization.

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WCRG Global Research

ISSN: 3071-5636
PP: 01-13.

1. INTRODUCTION

1.1. Background

Additive Manufacturing (AM) is one of the radical changes in the manufacturing industry as it modified the way the products are constructed and innovated. The traditional manufacturing technique, milling, casting, turning, and injection molding, processes primarily depend either upon discarding the bulk of a solid block of material (subtractive manufacturing), or upon forming material under influence of molds and dies (formative manufacturing). Such conventional methods may need complicated tooling, have long setup durations and waste a lot of material especially during the initial stages of product development. Additive Manufacturing often referred to as 3D printing, on the other hand, is simply a layer-by-layer additive process based on digital Computer-Aided Design (CAD) model output. Rather than simply removing material by cutting or using special dedicated molds, AM simply deposits material where geometry and internal structures require it, and it gives excellent control. This is a tool-free, fully digital production process which enables extremely complex shapes, internal cavities, lattices and topology-optimal designs to be produced that were challenging or impossible to make with conventional methods. Also, AM greatly minimizes the process of assembly by allowing the part consolidation when multiple parts may be assembled in one printed unit. Physical tooling changes to digital workflows will also reduce product development times, increase the ability to speed up prototyping, and allow increased customization. Thus, the emerging use that Additive Manufacturing is gaining, rather than being called as an alternative method in production, is a revolutionary technology that is redefining design philosophy, manufacturing economics, and strategies in global supply chains.

1.2. Evolution of 3D Printing Technologies

Since the pioneer of additive manufacturing technologies in the 1980s, Additive has made much evolution to include more than just polymer based systems such as early onset of additive technology up to the present-day application of metal and multi-material fabrication production technologies. The significant technologies have also played their own role in the development of 3D printing in the industries.

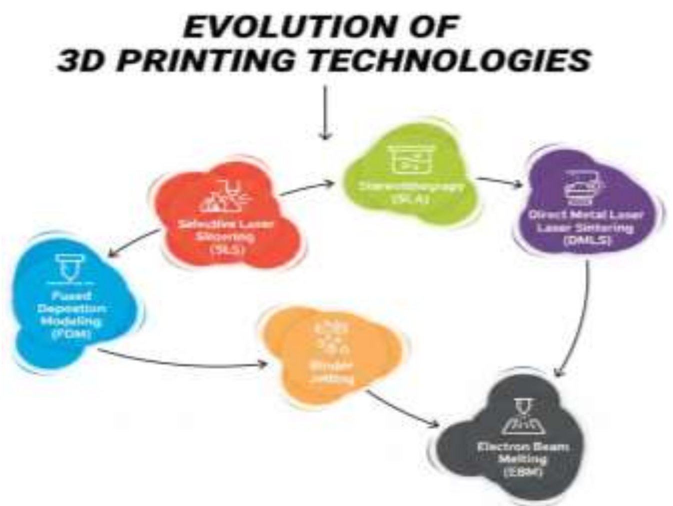

Fig 1 - Evolution of 3D Printing Technologies

ISSN: 3071-5636
PP: 01-13.

1.2.1. Fused Deposition Modeling (FDM)

One of the most popular and the most available 3D printing technologies is Fused Deposition Modeling. Invented during the late 1980s, FDM operates by pumping thermoplastic filament through a hot nozzle, and then positions layers of material atop each other in order to produce a solid object. It has been widely used in rapid prototyping, teaching and learning, and low-cost production because of its cheapness and simplicity to use. Even though FDM tends to provide a moderate surface finish and mechanical strength to the processes of industry, steady increases in materials and accuracy of printers have led to increased use in functional areas such as part production.

1.2.2. Selective Laser Sintering (SLS)

The technique of Selective Laser Sintering operates on a laser of increased intensity to melt together powdered materials, typically polymers or nylons into solid object forms. Each cross-sectional layer is made by the laser sinering powdered material selectively with the aid of the data of the digital design. It has not to be supported since natural support is provided by the surrounding unsintered powder during printing, SLS does not need to have support structures. This is very appropriate in the creation of complex geometries and interlocking components. It finds extensive application in aerospace, automobile and consumer product development.

1.2.3. Stereolithography (SLA)

The earliest commercial type of 3D printing technology was stereolithography, released in the 1980s. It is a curing method of treating liquid photopolymer resin to a hardened plastic layer via a ultraviolet laser, layer after layer. SLA is characterized by a high level of accuracy, a high level of surface finishing, and high level of resolution of details. It is typically used in medical modeling, dental applications and high-accuracy prototypes where dimensional accuracy is of serious importance.

1.2.4. Direct Metal Laser Sintering (DMLS)

Direct Metal Laser Sintering builds on additive metal manufacturing, in which a laser laser is used to melt metal powder grains. The process allows production of high density full strength metal components, which can be used in aerospace, automobile, and medical implantations. DMLS favors intricate interior pathways, lightweight sheetwork frameworks, and topology-opimized compositions, thus it can be useful in high-performance engineering.

1.2.5. Binder Jetting

In Binder Jetting, a liquid bonding material is added to a powder box in order to join particles of material in a series of coats. This process, on the other hand, does not involve the use of heat as laser-based systems use during printing, hence being faster and is applicable in the high volume production. The part is usually printed and then treated to curing or sintering in order to obtain complete strength. Metal parts, sand casting molds, and even full-color prototypes are being done using Binder Jetting.

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1.2.6. Electron Beam Melting (EBM)

Electron beam melting Electron beam melting is an additive manufacturing technique in the metal industry using an electron beam as the energy source to heat metal powder in a vacuum environment. EBM works at very elevated temperatures creating metal components that are not only dense and strong but with less residual stress. It has found certain applications especially with aerospace parts and orthopedic implants in which the performance and structural integrity of the materials is of much importance.

1.3. Role in Modern Manufacturing

With the advanced industrial development, modern manufacturing has become keen on lowering the lead time, mass customization, sustainability, and digitalization, where additive manufacturing (AM) is a good match. The short lead time is another essential competitive aspect where companies are taking part at an attempt to hasten the development of products and react fast to the fluid market needs. Additive manufacturing underpins this goal through the removal of complicated tooling and direct additive manufacturing of a final item, reducing the gap in between a concept and a finished product dramatically. This quickness in productions boosts innovation and gives organizations the capability of launching new products in the market more quicker than the conventional manufacturing system. The other characteristic of modern manufacturing is its customization. Consumers and industries are now demanding products as selections that meet their individualized functional, ergonomic or performance needs. In contrast to traditional mass-production regimes based on the use of standardized tools, AM enables changes in designs to be executed digitally without incurring significant cost reimbursement. This allows customized manufacturing of personalized medical implants, custom aerospace parts and personalized automotive parts, helping to honor the transition towards mass customization instead of mass production. Sustainability has also become a strategic manufacturing operation focus. Additive manufacturing helps in conservation by reducing wastage of material in the sense that its layer by layer fabrication process results in minimal waste of material, optimized material consumption and light weight designs that consume less energy in the process of using a product. Also on-site and local production minimizes transportation requirements and storage of inventories which further lessen the impact to the environment. Modern smart manufacturing systems are based on digital integration. AM is easily compatible with computer-aided design programs, simulation systems, cloud computing, and automated data monitoring systems. It is an online workflow that helps automatize it, control the process in real-time, and be traceable, in line with the principles of Industry 4.0. Consequently, additive manufacturing is central to the creation of elastic, production-efficient, and digitally linked production ecosystems within the contemporary industry.

2. *LITERATURE SURVEY*

2.1. Technological Advancements in Additive Manufacturing

The latest developments in additive manufacturing (AM) have opened up immense opportunities of designs through this process beyond the limiting factors of offline manufacturing processes, which are subtractive and formative. Increased design freedom and the ability to make very complex shapes, internal channels, lattice structures, and bio-inspired shapes that would be hard or even impossible to make by traditional methods are among the most striking advantages. AM also enhances material efficiency by creating parts in a layer-by-layer format thus reducing material wastage as opposed to machining processes which remove material by the solid block. Moreover, optimization methods for structures, such as topology optimization are being concurrently applied together with AM to generate lightweight and mechanically strong components. This synergy will enable engineers to strategically allocate material only where it is required to create a structure that will lead to optimized performance, minimization of weight and sustainability improvement.

2.2. Industrial Applications

Additive manufacturing has been popular in the aerospace sector as a technique of making lightweight lattice structures and complex components that make the whole aircraft lighter and consume less fuel. The reliability is also strengthened by the possibility to combine various components into one printed part to decrease assembly needs. AM has transformed manufacturing of patient customized implants, prosthetics and surgical guides used in healthcare. Patient imaging data can be used to design customized medical devices that enhance comfort, fit and clinical outcomes. Components in the automotive industry that are carried out through additive manufacture include fast tooling, prototyping and small-batch production. This cuts down product development cycles, shortens time to market and allows manufacturers to test design iterations in a cost effective manner within a short time span.

2.3. Economic and Supply Chain Impact

Additive manufacturing has already shown great economic advantages especially in the product development and supply chain management. Studies show that there has been a major decrease in the prototyping time so prototyping can be much faster in terms of design validation and innovation cycles are much lower. The fabrication by-layer technique reduces waste material when compared to conventional manufacturing, which results in cost-cutting and an enhanced environment. Also, AM increases supply chain resilience, contributes to decentralized production and on-demand manufacturing. This will help lower reliance on long, complicated global supply chains and help reduce inventory. Physical stock can be substituted with digital inventories, and thus local production of parts when required can be made, and there is a lower transportation cost, lead times.

2.4. Challenges Identified in Literature

Additive manufacturing has various technical and economical problems despite its benefits. The anisotropic behavior of mechanical properties of printed components is one of the main problems since the strength and stability of such components can depend on the orientation of the build. This may compromise the structural component reliability otherwise. The other difficulty is that the kind of materials that can be printable is quite limited relative to the traditional modes of production, though rise in material development is happening at a very rapid pace. The barriers to the mass uptake of the post-processing devices and industrial grade AM machines are also hindered by its high start-up costs, which is not easily accessible to the small and medium sized firms. Also, the absence of worldwide regulations on the quality control and testing and certification does not make the regulated industries sure; hence, making wider implementation difficult.

3. METHODOLOGY

3.1. Research Design

The research applies the comparative performance evaluation framework the study will take the form of a systematized analysis and comparison of Traditional Manufacturing (TM) and Additive Manufacturing (AM) in various technical, economic, and operational levels. The research design is designed in such a way that there is objective evaluation through testing both of the manufacturing strategies within the same functional needs and production environment. Some of the key performance indicators that were looked at in the comparison are the efficiency of the material utilization, time taken in production process, cost implication, flexibility in designing, mechanical performance and the impact on the environment. The framework has both quality and quantitative data obtained through the existing literature, industrial case studies, and secondary data sources to guarantee a complete assessment.

Traditional Manufacturing is investigated in the traditional way of machining, casting, and forming where a subtractive or formative manufacturing type and known workflow based on mass-producing are considered. Additive Manufacturing, on the other hand, is considered on the basis of its layer-by-layer methods of fabrication, integration of digital workflows and the fact that the process can be used to manufacture complex geometries with minimum tools. There are also lifecycle aspects that have been taken into consideration in the research design such as prototyping, scalability of production, implications of the supply and post-processing requirements. A comparative matrix is created in order to evaluate the strengths and weaknesses in such spheres as lead time, possibility of customization, the possibility to optimize structure, and their sustainability performance on the whole.

The paper also assesses constraints on its operation such as capital investment, skilled workforce and standardization of its operation and services. Through such systematic comparative methodology, the research will establish circumstances in which every of the manufacturing methods proves to be high in its performance. This model can guarantee that these conclusions do not represent the overall situation but rather they can be related to particular production conditions, quantities, and industrial applications. Finally, the research design helps to carry out the evidence-driven analysis to identify the ways in which Additive Manufacturing can be used as a supplement of Traditional Manufacturing or compete with it on the contemporary industrial conditions.

3.2. Performance Metrics

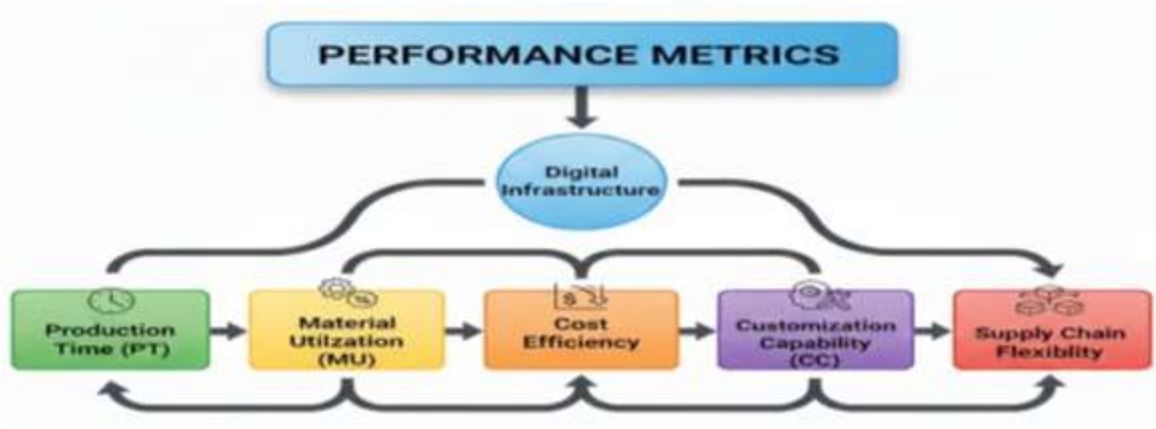

Fig 2 - Performance Metrics

3.2.1. Production Time (PT)

Production Time is the overall time it takes to produce a component since the time thereafter has been completed in designing, and delivery of the final goods. This incorporates the set up time, preparation of the tools, manufacturing and after processing. Traditional Manufacturing (TM) can be characterized by lengthy production periods because of fabrication of molds, setting up machining and assembling of products, particularly intricate geometries. Conversely, Additive Manufacturing (AM) can be used to decrease lead time by removing the need to prepare tooling as well as making direct products directly out of computer models. This is what makes AM especially beneficial when it comes to fast prototyping and low volume production batches.

3.2.2. Material Utilization (MU)

Material Utilization indicates how well the raw material is used to make a completed product. Regular Manufacturing operations especially machining which is subtractive in nature normally produce a lot of solid waste as chips and scrap. Additive manufacturing however does it in stages, one layer at a time depositing the material where it is needed. This leads to significantly reducing material waste and better efficiency in resources particularly in manufacture of complex or lightweight structures.

3.2.3. Cost Efficiency (CE)

Cost Efficiency measures the economic feasibility of a production procedure taken into account the expenses of materials, labor, and machine cost, energy use, and scale of production. Mass production is usually more economical on Traditional Manufacturing as a result of economies of scale and stronger per-unit production speeds. It is however associated with increased initial tooling and start up expenses. Additive manufacturing is cost-effective in low volumes, custom, and prototyping because it removes the cost of tooling and lessens design iteration costs.

3.2.4. Customization Capability (CC)

Customization Capability will determine the adaptability of a production process to manufacture unique or design-related parts without much expense or time penalty. The Traditional Manufacturing process is generally subjected to the need to either get new tooling or process modification in case of design change that adds cost and time to the production. Additive Manufacturing, on the contrary, allows reaching high rates of customization because no physical tooling will be changed when changes need to be implemented right in the digital design file. This renders AM especially-appropriate when it comes to customized products, medical devices, and custom-made engineering elements.

3.2.5. Supply Chain Flexibility (SCF)

Supply Chain Flexibility is defined as the resilience of a manufacturing plant to a change in demand, disruption, and logistical problems. The traditional Manufacturing is usually based on historic production centers, massive stock, and long supply chains. Additive Manufacturing improves the resilience of the supply chain by making on-demand production decentralized and becoming increasingly closer to the point of use. The digital inventory systems save on the physical inventory, lessen the transportation distance, and increase the sensitivity to market trends or unforeseen supply problems.

3.3. Analytical Model

The analytical model formulated within the research is aimed at giving quantitative comparisons between Traditional Manufacturing (TM) and Additive Manufacturing (AM) in terms of cost set up and working efficiency. The production cost is summed by weighing four main aspects of cost of production, namely, material cost, labor cost, machine cost, and overhead cost. Material cost is the raw materials used to manufacture the component which takes into consideration the waste and scrap rates. Wage is the labor cost that relates to machine operation, oversight, assembly and post processing aspect. Machine cost reflect equipment related cost which includes them in terms of depreciation, maintenance and energy use and also running time. The indirect expenses that constitute overhead cost are facility management costs, administrative support costs, utilities costs and quality control costs. These four cost aspects are added together to allow the model to calculate the total cost of manufacturing using each of these two methods and thereby be able to draw a systematic and transparent comparison of TM and AM when both are put under related conditions of production. Besides the cost-comparing, the analytical model compares efficiency enhancement in the two manufacturing modes. Efficiency is calculated as the percent change in some chosen performance figure like production time or material consumption when changing Traditional Manufacturing to Additive Manufacturing. This is computed by through subtracting the AM value to TM value and dividing the result of the calculation by the TM value and multiplying by a hundred percentage. The formulation gives a normalized way of measuring the improvement in performance and can be objectively compared with any scale. The positive percentage value represents the performance improvement, which was obtained with the help of AM, whereas the negative figure is a sign that TM is more effective in this particular performance measure. This analytical framework, in general, gives trade off between economic and operational evaluation as both cost competitiveness and process-efficiency are going to be measured methodologically on the scale. The model facilitates evidence-based decision making processes since it can be used to establish circumstances in which either TM or AM can deliver quantifiable benefits in industrial settings.

3.4. Experimental Framework

The experimental model of the given research is meant to furnish the structured and industry-related contrast of Traditional Manufacturing (TM) and Additive Manufacturing (AM). A sample population of 50 manufactured components was picked, as the sufficient amount of data. Such elements were spread to three key industrial areas, i.e. aerospace, automobile and healthcare. These industries have been chosen purposefully, and they are reflective of varying production needs, regulatory frameworks as well as performance demands. Typical aerospace component requirements include lightweight structures and high strength to weight ratios, automotive components typical focus on cost efficiency and scalability of production and clinical component requirements are usually quite customized and precise. This cross-industry sample enables the research to have a wider angle of manufacturing performance when using diverse conditions of operation. Each component had important performance data collected in a systematic manner; these were production time, overall manufacturing cost, and percentage of material waste. Measurement of production time was done through production time phases such as design preparation, setup, fabrication and post processing stage to cover full time assessment. The cost information was summed up by using the data of material costs, labor costs, machine costs, and overhead costs. The percentage of waste in materials was determined by dividing the weight of the raw material used by the weight of the final component giving an indication of efficiency in resources. TM and AM components geometries and functional requirements were chosen in a similar way where feasible in order to be consistent. Standardized measurement procedures were used to record the collected data so as to reduce bias and have comparability across industries. The trends, variations and performance differences were determined using statistical analysis techniques to establish the variations between the two manufacturing methods. With the incorporation of different industries and the use of metrical consistency in the evaluation of the corresponding results, the experimental model offers a solid empirical foundation on the relative merits and drawbacks of Traditional and Additive Manufacturing in the real-life production settings.

4. RESULTS AND DISCUSSION

4.1. Performance Comparison

Table 1: Performance Comparison

Parameter	Improvement (%)
Production Time Reduction	48%
Material Waste Reduction	52%
Cost Efficiency Improvement	35%
Customization Capability	70%
Supply Chain Flexibility	60%

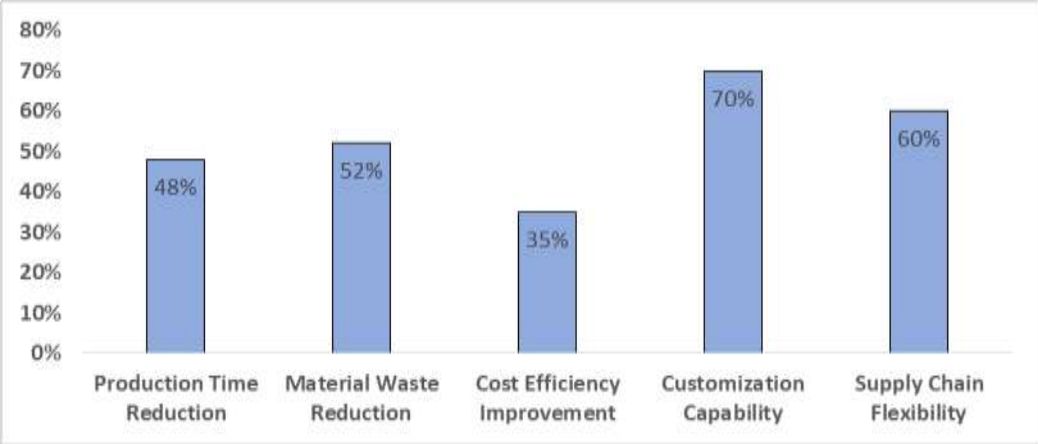

Fig 3 - Performance Comparison

4.1.1. Production Time Reduction (48%)

The findings show that the production time is reduced by 48 per cent when Additive Manufacturing (AM) is used in lieu of Traditional Manufacturing (TM). This has been greatly enabled by the fact that it has removed the need to use tools, the set up process has been cut down and also large geometries can be fabricated with a single build. In conventional processes, much time is taken to partially mold fabrication, machining set-up and assembly processes. AM simplifies this process by simply creating parts based on digital designs eliminating the need to take design to prototype and produce small production batches. This is a time advantage that is especially important in a business with high rates of product development and time-to-market.

4.1.2. Material Waste Reduction (52%)

Additive Manufacturing helped in cutting down material waste by 52%. The conventional subtractive processes produce a lot of scrap material as they undergo machining and finishing. On the contrary, AM is able to deposit material only where it is structurally needed and the utilization of material is much more efficient. This is because, besides decreasing the costs of raw materials, this measure improves the environmental sustainability as the cost of resources and disposal is reduced. It is also particularly applicable in high cost materials e.g. aerospace grade alloys and medical grade metals.

4.1.3. Improvement of Cost Efficiency (35%)

The research found that there was an enhancement in the overall cost efficiency with AM by 35% in the chosen production cases. Even though AM systems can be associated with an increase in initial machine cost, they can decrease the cost through the decreased tooling cost, decreased material wastage, less labor input during the assembly process, and more quickly designed products. The economic advantages are most eminent in the low- to medium-volume production and custom manufacturing where the conventional tooling would have been very high.

ISSN: 3071-5636
PP: 01-13.

4.1.4. Customization Capability (70%)

The ability to do customization improved the most the most by 70%, which also signifies the power of the Additive Manufacturing. Re-designs can be applied directly in the form of digital models without requiring a different tooling or process modification. This allows quick response to certain client needs especially in medical implants, specialized automobile components and aircraft parts. The AM can easily be modified which contributes immensely to the product customization and innovation of design.

4.1.5. Supply Chain Flexibility (60%)

The decentralized production characteristics of Additive Manufacturing enhanced flexibility of supply chains by 60 percent through the on-demand production. AM enables manufacturing nearer to the point of usage, unlike the conventional centralized systems of production that require huge inventories and long logistic lines. Electronic inventory management lowers storage expenses and lowering transportation duration and responsiveness towards the market changes or disruption of supply. It is this flexibility that enhances the overall supply chain resiliency and operational flexibility.

4.2. Analysis

The findings of the research show clearly that the Additive Manufacturing (AM) offers significant performance benefits with respect to the ability to customize and flexibility in the supply chain. The large increase in customization indicates the digital-based model of production at AM, where the changes in design can be made rapidly, and new tooling, molds, and significant changes in the process are not required. This flexibility enables the manufacturers to quickly adjust to any changing customer needs which means that mass customization can be done without the large rise in production costs and lead time. Healthcare and aerospace industries particularly are particularly beneficiaries of this ability as they tend to need highly specialized parts to meet either a functional or patient specific requirement. Another significant aspect of improvement found in the results is supply chain flexibility. Traditional Manufacturing is generally relying on centralized plants, large storage areas, and complicated logistics systems. Contrarily, AM encourages decentralized and on-demand manufacturing that minimizes use of long supply chain and cost of inventory holding. Digital files may be moved all over the world and produced at regional location, thereby reducing delivery time and responsiveness to demand changes and demand disruptions. This decentralised model increases the stability of operations and minimises the risks related to shipping delays, political unpredictabilities and shortages in materials. The presence of material waste reduction is also especially significant, and it is one of the most quantifiable benefits of AM. As the process is additive in nature, only necessary material is deposited as compared to subtractive manufacturing where unwanted material is removed out of solid blocks. This results to greatly enhanced material utilization rates and less scrap. Another factor that the environment must not be ignored is that less waste results in the sustainability agenda and less amount of resources. All in all, this analysis proves that, in addition to enhancing operational efficiency, Additive Manufacturing can be used to address strategic goals associated with sustainability, responsiveness, and product customization.

5. CONCLUSION

The concept of additive manufacturing (AM) is radically changing the modern system of manufacturing organizations, providing an unprecedented ease of design, efficiency of operations, and flexibility of the supply chain. The results of this research affirm that AM helps to boost a performance on the production on many dimensions and specifically, to decrease the amount of material waste, reduced production time and increase the ability to customize the product. As opposed to older methods of subtractive and formative production, AM allows the production of complex geometrical shapes and designs, internal lattice structures as well as topology-optimized structures, which were in the past, impractical or even impossible to create. The benefits of this go beyond just structural performance, by enhancing lightweighting schemes in aerospace and automotive as well as other industries where weight reduction can have a direct effect on energy consumption, operational cost-savings. The paper further illustrates that AM Corp. has a rich impact on supply chain responsiveness by producing models that are decentralized and on-demand. With the substitution of the material inventories with the digital design files, the manufacturers will be able to minimize the storage needs, decrease the costs of transportation, and be able to react better to the changes in the market or any other disturbance worldwide. This digitalisation is highly consistent with the requirements of smart manufacturing and improves operational resiliency in general. Moreover, the decrease in the number of materials waste that could be seen in the analysis identifies the benefit of AM to the environment, which contributes to sustainability objectives and resources optimization strategies. Although these are positive, there are a number of challenges. The problems involved in standardization of processes, consistency in quality, scalability to mass production and the high initial capital expense of machines still remain at a barrier to mass adoption by industries. Inconsistency of mechanical properties and lack of material is also a factor that needs additional technological development. Nevertheless, the continued introduction of new innovations in the field of automation, artificial intelligence, real-time monitoring, and digital twins are likely to eliminate most of these drawbacks. AM execution under Industry 4.0 will increase the process optimization, predictive maintenance, and data-driven quality verification; it will improve the reliability and industrial trust. The combination of traditional manufacturing with additive processes in the form of hybrid manufacturing models seems to be the most viable route to be taken. These models capitalize on the strengths of the two processes, where complex, simplified or even customized components are developed using AM, whereas high volume and low-cost production is achieved through the conventional processes. This is a moderate approach that ensures the greatest competitiveness and least operation risk. Innovation in materials, enhanced repeatability of the process, the decreased cost of machines and the elaboration of the whole global standardization systems should be put in the focus of future research. The consideration of these spheres will enhance industrial scalability and facilitate the further development of additive manufacturing as one of the main pillars of advanced manufacturing systems.

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