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ADDITIVE MANUFACTURING AND SUPPLY CHAIN: A REVIEW OF THE STATE OF THE ART

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ABSTRACT

The thesis comprehensively analyzes the revolutionary impact of additive manufacturing technology on supply chain management. By studying the principles, key technologies, and application advantages of additive manufacturing in different industries, it explores how this innovative technology can simplify logistics operations, reduce transportation costs, and achieve on-demand production and personalized customization, thereby improving customer satisfaction. The thesis also focuses on the potential impact of additive manufacturing on traditional supply chain models, including its contribution to environmental sustainability and waste reduction. Additionally, we examine the challenges of implementing additive manufacturing, such as supply chain integration, technology constraints, human resource requirements, and regulatory considerations. We also demonstrate successful implementation strategies and results through practical case studies.

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1. INTRODUCTION

A. Brief Explanation of Supply Chain

Supply chain refers to a complete logistics system composed of various links such as raw material suppliers, manufacturers, distributors, and end consumers. It covers a series of processes and activities from raw material procurement, production and manufacturing, logistics and transportation, inventory management, and channel distribution to final sales of products. The goal of the supply chain is to achieve efficient production and circulation of products through reasonable planning and coordination of various links, in order to meet market demand and provide high-quality products and services. An efficient supply chain can reduce costs, improve production efficiency, shorten delivery times, and thus enhance the competitiveness of enterprises (Bouchenine Abderrahmen & Abdel-Aal Mohammad A.M.,2023). At the same time, supply chain management also needs to pay attention to factors such as risk control, information sharing, establishment and maintenance of partnership relationships, and adaptation to the constantly changing market environment. By optimizing the operation of the supply chain, enterprises can achieve maximum utilization of resources, improve customer satisfaction, and gain greater advantages in market competition.

B. Brief explanation of additive manufacturing

Additive Manufacturing (AM), sometimes referred to as 3D printing technology, is a fast manufacturing technique based on digital models that makes it possible to convert digital ideas into tangible goods by continually adding materials to an object's structure layer by layer. With additive manufacturing, materials are added layer by layer in a precise sequence and proportion to create components with intricate forms and structures, in contrast to typical subtractive manufacturing processes like milling, turning, grinding, etc.

Using the product's digital model as a starting point, computer-aided design (CAD) software is used to create 3D models for additive manufacturing. The additive manufacturing equipment is then equipped with the modeling data. Then, layer by layer, the additive manufacturing equipment applies the raw materials in the form of powder, wire, or liquid to the work platform while adhering to the predetermined process parameters. Alessio Ronchini, Antonella Maria Moretto, and Federico Caniato (2023) state that a number of methods, including heating, hot melting, and curing, are employed to forge a link between the material layers. After construction is finished, excess material or the support structure is removed, and the finished product is heat-treated or undergoes extra processing before being surface-treated.

The benefits of additive manufacturing are numerous. It allows for highly personalized customisation in the first place, allowing each product to be made specifically to meet the demands of the buyer. Second, compared to the traditional manufacturing method, which involves several tests and revisions, additive manufacturing can swiftly iterate product design while saving money and time. Furthermore, more intricate forms and structures like honeycomb structures, internal channels, and cavities may be produced by additive manufacturing, which is crucial for particular applications. Moreover, additive manufacturing may minimize waste production, maximize material efficiency, and be ecologically benign.

In many different sectors, additive manufacturing is frequently employed. Using additive manufacturing technology, the aerospace industry can produce lightweight, highly-strength spacecraft components; the medical industry can produce artificial joints and medical devices that are tailored to each patient's unique characteristics; the automotive industry can produce automotive parts quickly, test them, and optimize their performance; and the architectural field can produce buildings with intricate structures and functions exactly as intended by the architect (Danfeng Xie, Jian Xin,Hongyan Wang & Lei Xiao,2023). Furthermore, additive manufacturing finds extensive use in contemporary industrial design, cultural and creative production, among other domains.

Generally speaking, traditional manufacturing has new chances to evolve as a result of the introduction and use of additive manufacturing technologies. In addition to offering a more adaptable and effective production process, it also fosters innovation and individualized customisation. Additive manufacturing technology will become increasingly significant in the future and a major driver of industrial development as a result of the ongoing advancements in digital technology, materials science, and manufacturing processes.

C. Importance of logistics in supply chain management

A key component of supply chain management is logistics. A supply chain is a set of interconnected operations that include obtaining raw materials, producing and processing goods, managing warehouses, organizing logistics, and distributing goods with the goal of moving goods or services from suppliers to end users. Logistics, the central component of supply chain management, is in charge of moving items from one end of the chain to the other and tightly tying together every link.

In the beginning, logistics could provide quick logistics distribution to ensure that products can be delivered to customers on time. Through sensible transportation planning and logistics network structure, logistics may establish effective collaborative work between all supply chain nodes, reduce supply chain disruption or production slowdown caused by logistical delay, and finally increase end customer satisfaction.

Logistics has the potential to lower the management of supply chains expenses. The cost of logistics connections like transportation, warehousing, and packing may be decreased by streamlining the logistics process and selecting the most cost-effective mode of transportation. Logistics is a crucial cost component in the supply chain. Additionally, via sensible route design and integration of cargo transportation demands, logistics may lower the total cost of the supply chain, decrease the transportation distance and empty load rate, and enhance the utilization rate of logistical resources.

For information flow and supply chain visualization to be realized, logistics is crucial. Order processing, inventory management, and logistics process tracking and monitoring are all made possible by the logistics link with the aid of an information system. With the help of this, supply chain managers can better adapt and optimize the chain's operational procedures in a timely manner, increase the chain's flexibility and response time, and lower the level of uncertainty in the logistics and inventory links (Calignano Flaviana & Mercurio Vincenza,2023).

Additionally, logistics may raise the added value of products and offer services with additional value. The competitiveness of items on the market may be increased by providing them with logistical services including package protection, branding, and user manuals. In order to satisfy clients' demands for specialized and individualized logistics, logistics may also provide clients specialized distribution services such expedited delivery, warehousing, LCL, etc.

D. Thesis statement: Exploring the impact of additive manufacturing on the supply chain.

Using layers of material stacking, Additive Manufacturing (AM) is an advanced manufacturing technology that creates components or products. It offers several benefits over traditional subtractive manufacturing, including no mold, great customizability, and quick response to client requests. The supply chain has been significantly impacted in recent years by the continued advancement and use of additive manufacturing technologies (Patil Himali, Niranjan Suman, Narayanamurthy Gopalakrishnan & Narayanan Arunachalam, 2023). Examining the effects of additive manufacturing on the supply chain is crucial for this article. Thorough investigation of the effects of additive manufacturing on the supply chain will enable us to better comprehend and manage this technology's growth trend, as well as enhance the supply chain's flexibility and competitiveness.

2. Literature Review

A. Overview of Additive Manufacturing

1. Definition and principles of additive manufacturing

Additive Manufacturing (AM) is a state-of-the-art manufacturing process that involves layer-by-layer construction of complicated components or products. In contrast to conventional subtractive manufacturing, additive manufacturing creates tangible physical products from digital models by using computer-aided design (CAD) software. (Garmabi and others, 2022). Its basic idea is to continually build or harden layers of material on a virtual work platform in order to generate the required three-dimensional shape.

The following stages can serve as a summary of additive manufacturing's fundamental ideas:

1. High-precision data acquisition: To start, high-precision data of the target item can be obtained by using computer-aided design software or 3D scanners. The object's geometric traits and form are among these data.

2. Digital design and modeling: Based on the collected data, digital design and modeling are carried out using CAD software. The object's form, composition, and functionality may all be carefully controlled and altered during the modeling process.

3. Slice and path generation: Using CAD software, the object model is split into a number of horizontal slices, and each slice's stacked path is produced. The additive manufacturing equipment will follow these patterns to build up or harden the material on each slice.

4. Material accumulation or solidification: The additive manufacturing machinery starts to collect or solidify the material layer by layer under the direction of route creation. The material can be metal powder, plastic, ceramic, etc., depending on the various additive manufacturing technologies used. These materials can be treated by

spraying, heating, solidification, and other techniques (Manco Pasquale, Caterino Mario, Rinaldi Marta & Fera Marcello,2023).

5. Post-treatment and surface treatment: These are often necessary once material buildup or solidification is complete. To get the finished product, this entails eliminating support structures, applying heat treatments, smoothing surfaces, and other procedures (Patel Pinkesh, Defersha Fantahun & Yang Sheng, 2022).

By turning digital models into tangible items, additive manufacturing technology makes it possible to produce goods quickly, precisely, and to a customer's specifications (Sun et al., 2023). It is employed in many different industries, including as consumer products, aerospace, medical devices, and automobile manufacture. We anticipate that additive manufacturing technology, with its ongoing advancements and innovations, will significantly alter traditional production and open up previously unimaginable industrial opportunities (Mobarak et al., 2023).

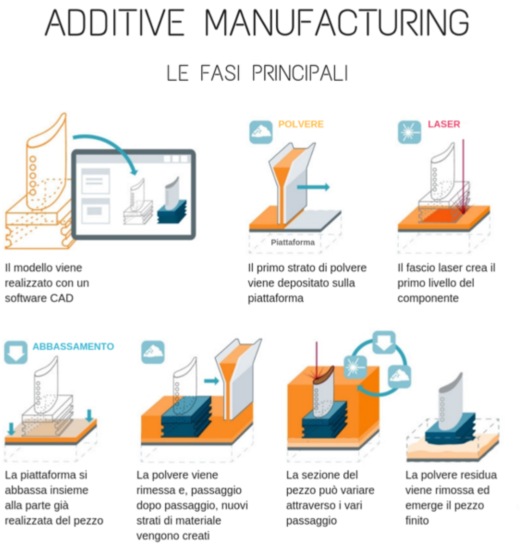

Figure 2-1 Process of AM from paddock.it

2. The essential tools and procedures for additive manufacturing.

A wide range of technologies, each with its own special materials and methods, are included in additive manufacturing. Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA) are three of the most widely utilized technologies.

Fused Deposition Modeling (FDM):

In FDM, a well-liked additive manufacturing method, thermoplastic materials are extruded via a heated nozzle. The material is placed layer by layer on the construction platform, cooling and solidifying to create the final result. The cost-effectiveness and versatility of this technique make it frequently employed. It may be used to a broad range of materials, from sophisticated composites with integrated carbon fiber to ordinary thermoplastics like PLA and ABS (Crump, 1991).

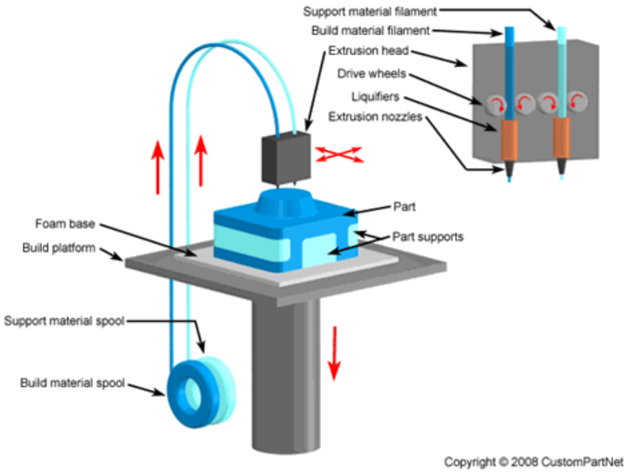

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Figure 2-2Fused Deposition Model(FDM) from CustomPartnet

Selective Laser Sintering (SLS):

In SLS, powdered material—typically nylon or polystyrene—is sintered using a laser to fuse the particles into a solid structure. Since unsintered powder maintains the product while printing, SLS does not require support structures like FDM does. This has proven beneficial in applications like the aerospace and automotive sectors, enabling more complicated geometries. (Deckard, 1989).

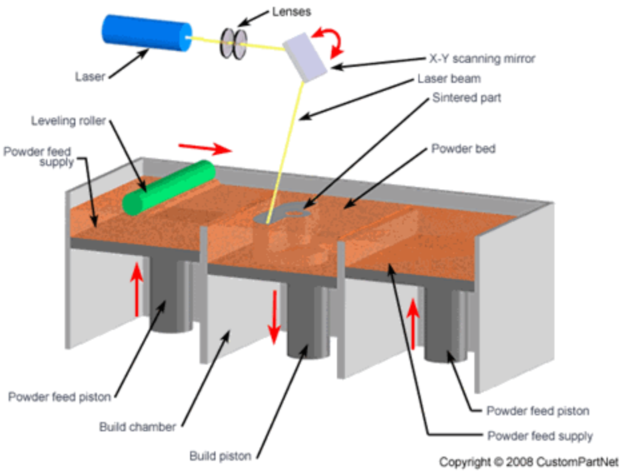


Figure 2- 3 Selective Laser Sintering (SLS) from Custompartnet.com

Stereolithography (SLA):

Photosensitive resin is cured and solidified with an ultraviolet laser in SLA. Every layer, the build platform dips into a resin tank, and while the laser tracks the part's cross-section, a tiny layer of resin hardens. SLA is renowned for producing parts with high resolution and smooth surface finishes, making it suitable for dental, medical, and prototyping applications (Hull, 1986).

A pioneer in rapid prototyping technologies, is renowned for its precision in crafting intricate polymer components. Developed by 3D Systems, Inc. in 1988, based on the innovative work of Charles Hull, this technique employs a finely focused UV laser to shape successive layers of a 3D object within a vat of liquid photosensitive polymer. The process involves the laser solidifying the polymer in the desired pattern while keeping the surrounding areas in liquid form. After each layer is completed, a blade sweeps across to ensure an even surface before the addition of the subsequent layer. The build platform descends incrementally, typically by 0.003 to 0.002 inches, allowing for new layers to be superimposed over the previous ones. This cycle of tracing and leveling continues until the entire structure is fabricated. Upon completion, the object is raised from the vat to allow drainage. Hull explained in 2023 that any residual polymer is cleaned off, often followed by a final UV post-cure in an oven. Support structures are then removed, and the part undergoes final finishing touches such as polishing or sanding to achieve the required surface texture.

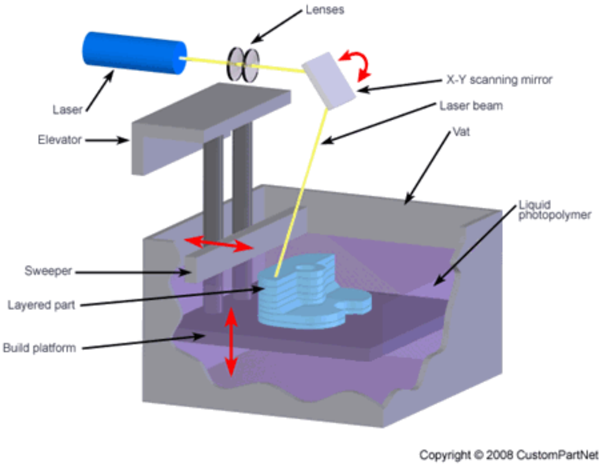


Figure 2- -4 Stereolithography (SLA) from CustomParNet

Each of these technologies follows a similar workflow:

a. Design: All additive manufacturing processes begin with a digital model, typically created in a CAD software. The surface geometry of the three-dimensional object is then described by this model once it has been transformed into a standard tessellation language (STL) file.

b. Pre-processing: A slicing program imports the STL file, slices the model into a number of thin layers, and creates the toolpath needed for the printer to create each layer.

c. Printing: The printer executes the process specific to its technology, adding materials layer by layer according to the sliced model.

d. Post-processing: After printing, objects often require cleaning, support removal, and surface finishing to achieve the desired quality and functionality.

The selection of a particular additive manufacturing process depends on several factors, including material requirements, mechanical properties, surface finish, precision, and cost. The rapid evolution of these technologies has expanded their applications, challenging traditional manufacturing in terms of speed, cost, and customization (Gibson et al., 2015).

Research continues to optimize these processes for industrial applications, focusing on improving material properties, reducing waste, and increasing production speeds (Vaezi et al., 2013). As these technologies mature, they promise to unlock new potentials in manufacturing, allowing for greater design freedom, sustainability, and efficiency (Wohlers et al., 2019).

3. The benefits of additive manufacturing and its possible uses in a range of sectors

Due to its benefits, including shorter lead times, design freedom, and production flexibility, Additive Manufacturing (AM) has many potential applications across a wide range of sectors.

The first benefit of additive manufacturing is its great production flexibility. With additive manufacturing, digital design documents may be instantly translated into physical components without the need for intricate molds and tooling, as opposed to traditional production techniques. This enables producers to react swiftly to shifts in consumer demand for customized or small-batch production (Lau Jjincheng, 2022). Moreover, additive manufacturing can do mixed production with several varieties in small batches, which significantly increases production flexibility and efficiency.

The major industries in the market for applications of additive manufacturing technology are aerospace, biomedical, and car manufacturing. Additive manufacturing is becoming a commonly utilized technology in the aerospace industry because of its distinct application benefits, which allow it to satisfy production needs of high accuracy, complicated geometries, and small quantities. In the vital subject of biomedicine, devices such as dental crowns, braces, hearing aids, and cranial implants have been effectively employed. (News.orangecds 2022).

Additive manufacturing technology offers a new approach to lightweight, flexible body design and production in the automotive industry. Along with decorations and handicrafts, cultural creativity is progressively being used to a wider range of boundaries. For instance, the Belgian business Materialize creates unusual materials and stylish clothing with intricate geometric designs using 3D printing technology(Figure 3.1)

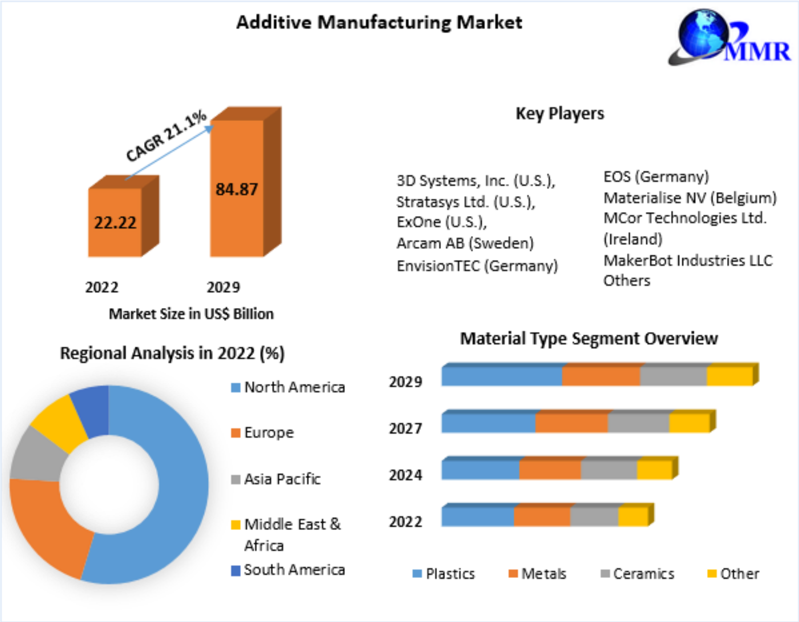


Figure3-1 Additive manufacturing market from Scopusdatabase

Aviation

Airbus, Liebherr of Germany, Chemnitz University of Technology, and other institutions developed 3D printed aircraft spoiler hydraulic manifold with Ti64 titanium alloy as the material, using SLM technology to manufacture, and other hydraulic parts are assembled, to achieve the performance of the hydraulic system to improve and optimize the fuel efficiency of the aircraft (Wu and David,2022). An A380 aircraft loaded with the first additively manufactured hydraulic part has been successfully test-flown. Airbus has also standardized its ULTEM 9085 additive manufacturing material and can use it while making aircraft components for the A350 XWB aircraft.

U.S. Potomac Design will be LSF technology applied to the U.S. Navy aircraft engine parts wear repair, the realization of the failed parts of the rapid, low-cost regeneration of manufacturing.

Xi'an Platinum Lite utilizes SLM technology to solve complex structural problems such as random inner runner, complex thin walls, skeleton weight reduction, complex inner cavity, multi-part integration, etc., and can provide more than 8,000 pieces of complex and precise structural parts for the aerospace field every year (Yang and Wu ,2022).

Under the attack of Beihang, Xi'an Platinum Lite, and other institutes and enterprises, titanium alloy main windshield integral window frame.(Melissa Orme,2020) landing gear integral support frame, central wing edge strip, and other key parts have been successfully developed through metal additive manufacturing technology, with a total of 23 additively manufactured parts loaded, which greatly improves the localization rate of C919 (Marco and Hu,2023).

The First Academy of Aerospace Technology successfully realized the rapid development of titanium alloy core stage binding support test pieces for the Long March 5 rocket by using the laser synchronous powder feeding additive manufacturing technology, which is also the first time that the laser synchronous powder feeding additive manufacturing technology is applied in the key components of large-scale main bearing segments (News China,2022).

Automotive

One of the global industries with the highest levels of competition is the automotive sector. Every day, new design and market trends appear, necessitating the development of new manufacturing techniques to meet automotive industry standards. By reducing product design and development time, providing production flexibility, and producing optimal automotive components and customized vehicle products on demand, additive manufacturing, or AM, provides this sector a considerable competitive edge. Using AM on soft assembly equipment or specialized machines to make car components is beneficial for the automotive production industry. The design and direct manufacture of automotive components that are optimized for vehicle performance, along with the creation of bespoke assembly tools to increase productivity, are made possible by AM's freeform capacity（Vasco, 2021）.

We can see from the picture below (Figure3-2) the current and future additive manufacturing involved in the automotive field.

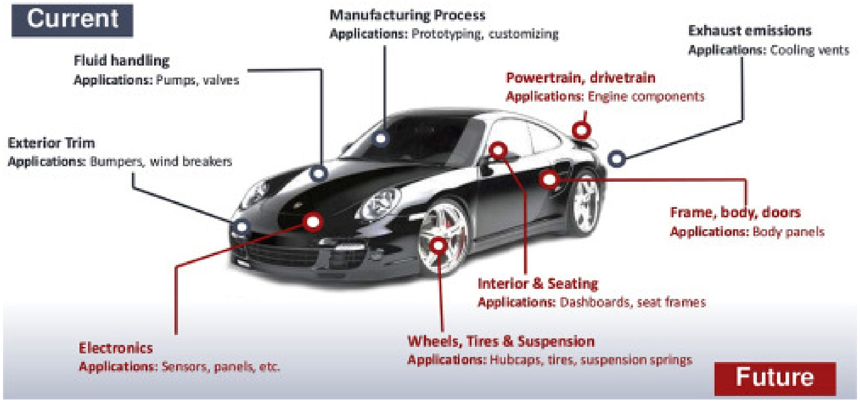


Figure 3-2 AM in automotive field (ScienceDirect database)

Biomedical Application

The production of scaffolds and medical devices by additive manufacturing, or 3DP, for the purposes of medication administration, ex-vivo tissues, regenerative medicine, and tissue engineering has garnered a lot of interest in recent years. While many biomedical applications are still in the development stages, a few medicinal devices—namely, ZipDose, Pharmacoprinting, powder bed fusion, HPAMTM, bio-printer, and inkjet printer—have obtained FDA clearance. (In 2017, Ramakrishna and Singh)

Using additive manufacturing technology, researchers at the Functional Materials Laboratory at the Federal Technical University of Zurich have created a resin-silicon heart that can sustain roughly 3,000 heartbeats for 30 to 45 minutes.(OrangesNews.nd)

Four primary forms of AM are used in 3D bioprinting technologies: droplet, resin, extrusion, and laser-assisted systems. The stability of the process is greatly impacted by the composition and ambient conditions of the bio-ink used in the 3D bioprinting of soft constructions. In the following subsections, each of the four primary 3D bioprinting technologies' essential details have been covered. Even with all of its advantages, AM technologies are still rarely employed in mass production when patient-specific implants are needed. In biomedical applications, additive manufacturing typically consists of hard and soft constructions for orthopedic implants, tissue engineering, and clinical medicine.

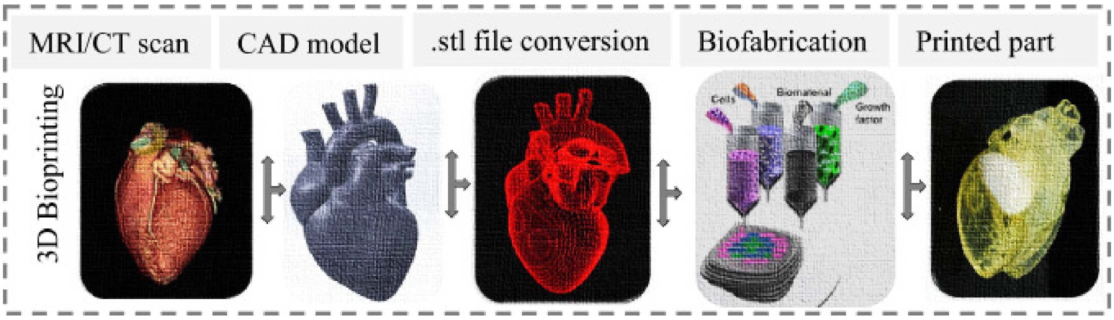


Figure 3-3The basic process steps in 3D bioprinting. Copyright 2020 Elsevier

B. Traditional supply chain

1. Overview of the supply chain and its main components and processes.

As stated by Lee and Billington (1995), the primary objective of supply chain management is to "optimize the performance of the chain to add as much value as possible for the least cost possible." This includes production, distribution, and procurement. Stated differently, the objective is to establish a connection between all supply chain participants and foster collaborative efforts within the company to optimize supply chain efficiency and maximize benefits for all stakeholders (Finch 2006). Industry adoption of supply chain management techniques has been rising since the 1980s. Numerous definitions are put forth, and the idea is examined from a variety of angles. Regarding supply chain management literature, however, Cousins et al. (2006), Sachan and Datta (2005), and Storey et al. (2006) offered a great overview. These studies defined the term, principles, nature, and evolution of supply chain management (SCM) and critically assessed developments in the theory and practice of SCM. They also demonstrate how widely study is being done in this field worldwide..

Gunasekaran and McGaughey (2003) broadened the definition of supply chain management (SCM) to encompass elements of Total Quality Management, including organizational structure, training, behavioral challenges, and management commitment, in addition to material management, partnerships, and information technology. Supply chain management (SCM) depends on an understanding of the integration process, which is vital to a business's sustainability. Mouritsen et al. (2003) explored and illustrated the degree to which the supply chain's "environment" and the power dynamics among its players influence the management of the chain, challenging the basic claim that "the more integration (wider the scope) – the better the management of the chain" is always accurate. The authors offered several management techniques and tools for analyzing successful SCM initiatives.

The use of more sophisticated methods for SCM optimization and decision-making, including as simulation, artificial neural networks, and fuzzy thinking, is also addressed, suggesting that research is not just restricted to data analysis and hypothesis testing. While Chiu and Lin (2004) showed how the ideas of cooperative people and artificial neural networks (ANNs) can work together to enable collaborative supply chain planning (SCP), Koh and Tan (2006) used fuzzy logic rules for supplier performance analysis and monitoring based on product quality and delivery time criteria (Shukla, 2019).

The literature review states that supply chain management has been examined from a systemic viewpoint, taking into account the systemic elements of the relationships among supply chain participants.

2. Explanation of the traditional supply chain model

The conventional supply chain model depicts an organizational structure with the product maker at its core that interacts and transmits materials and information in a linear, one-way flow. The producer is positioned at the center of the model, and via a sequence of connections in the manufacturing process, the raw material is changed into the final product, which is then given to the customer (Fernando, 2023). To help businesses compete in the marketplace, traditional supply chain management essentially combines the management of supply and demand both within and across organizations (Diggipacks, 2023).

When processing business and customer orders, the traditional supply chain follows a few fundamental steps. We will go into great detail about the stages of the traditional supply chain in the following:

Step 1: The collection of raw materials

At that time, all of the raw materials—which might include one or more elements—necessary to manufacture and produce the final product are gathered..

Step 2: The collection of materials from suppliers

The basic steps of the conventional supply chain include the stage of material collection from suppliers. which, through the proper suppliers, allows the production or manufacturing process to obtain the necessary raw materials.

Step 3: Production

At this point, the products are produced following the identification of the raw materials needed for the workday and their procurement from suppliers.

Several pieces of equipment may be used in this process to complete the products and produce a finished good that can be given directly to customers.

Step 4 | Distribution to the customers

It is a component of the conventional supply chain, which is used to deliver manufactured goods to consumers or retailers.

Step 5: Final Consumer Consumption

It is the final step of the process where retailers or end users buy the completed goods directly from the manufacturer (Garmabi et al., 2022).

The majority of material and information flow in the conventional supply chain model is one-way. Suppliers provide raw ingredients to manufacturers, who then distribute completed goods to distributors and end users. Wijnia, Siert (2019). Maintaining control over each link's inventory and demand is also crucial at this time. Suppliers must supply raw materials by manufacturer needs, manufacturers must make in accordance with distributor needs, and distributors must sell and distribute by customer demands (Rausch-Phan & Siegfried, 2022). The seamless operation of the whole supply chain is ensured by this communication and movement.

But there are several disadvantages to the conventional supply chain paradigm as well (Verhoeven, 2021). It is typical to have excess or inadequate stock in the chain of supply due to the latency in information transfer and the partiality of information, and it is challenging to forecast changes in customer demand with accuracy. Furthermore, the supply chain as a whole is sluggish to adapt to the market's quick changes and demands for flexibility due to the linear process (2023).

Globalization and technological advancement have caused the conventional supply chain model to progressively change and get better. For instance, integrating cutting-edge technologies like artificial intelligence, big data, and the Internet of Things can allow for real-time data exchange and acquisition throughout the supply chain, enhancing its responsiveness and visibility. Ludoveka (2021)Additionally, there is a greater chance of resource and risk sharing as well as increased supply chain flexibility and efficiency when parties cooperate.

3. Challenges and limitations of the traditional supply chain

The typical supply chain model faces the issue of excess and shortfall inventory when it comes to inventory management. The old model's information transmission latency makes it challenging for supply chain actors to forecast changes in market demand with any degree of accuracy. This will quickly result in surplus inventory, which will waste money and raise storage expenses. Additionally, a stock shortage may result from a delay in information, which would impair the supply chain's regular operations and its ability to satisfy customer demands (Wang canyon, Su qin & Zhao ding, 2018).

The conventional supply chain model frequently struggles with high logistical costs and inefficient transportation (Calloway Cook, 2023). It is frequently challenging for supply chain partners to develop precise transportation plans and arrangements because of the opacity and inadequate flow of information, which leads to wasteful transportation and underutilization of vehicles. Furthermore, labor, fuel, and time expenditures associated with traffic congestion are some of the additional high costs associated with logistics (Sebastian Jungles, 2022).

Low storage efficiency and restricted storage capacity are issues with the typical supply chain paradigm (John Moss, 2022). It is frequently challenging for supply chain partners to develop correct inventory plans and storage layouts, as well as to achieve the shared and optimal usage of storage resources, because of the delayed and opaque information. As a result, storage space is wasted and operational efficiency is decreased (Emily Murphy, 2022).

The information latency and opacity, along with the sequential procedure and one-way flow mode, are the primary causes of the traditional supply chain model's limitations. Because of this, the supply chain finds it challenging to adjust to the market's quick changes and individualized demands (Bradley, 2021). Furthermore, the effectiveness and adaptability of the supply chain are also restricted by the absence of actual collaboration and sharing, which is caused by the comparatively autonomous interaction between the various parts in the network.

The "take-make-dispose" method of traditional manufacturing is its main focus. However, its continued viability is being questioned because to the volatility of resource prices, rising rates of consumption, and growing regulatory and environmental challenges (De Angelis et al., 2018). Flexible supply chains promote sustainability and ensure on-time delivery (Dwivedi et al., 2021). Converting to a circular economy presents a viable way to accomplish both environmental preservation and economic growth at the same time. This type of change is made feasible by transforming existing supply chains into CSCs through a holistic and all-encompassing strategy that encompasses the redesign of products, company structures, networks of supply chains, goods and data flows, and enablers (Bressanelli et al., 2019).But there are a number of obstacles and difficulties with the redesigning approach that need to be taken into account.

With the aid of cutting-edge technology and creative concepts, current supply chain management is enhanced to get beyond these obstacles and constraints (Nandi et al., 2021; Sawe et al., 2021). To enable supply chain players more correctly estimate and satisfy market demand, improve inventory management, and optimize warehouse layout, for instance, current information and data exchange may be provided via the deployment of technologies like the Internet of Things, large amounts of data, and artificial intelligence. In addition, supply chain collaboration and cooperation are becoming more and more crucial for enhancing the chain's overall flexibility and efficiency through the formation of partnerships and resource sharing (Agrawal et al., 2021). Conventional supply chain models are being shifted toward being smarter, efficient, and sustainable by these advancements and innovations.

4. Importance of an efficient and responsive supply chain for businesses

Maintaining a competitive advantage requires an efficient supply chain that maximizes resource utilization and reduces waste (Chopra & Meindl, 2016). As an illustration, Amazon's utilization of cutting-edge inventory management systems has established a standard for supply chain effectiveness (Ross, 2020). Moreover, Zara's capacity to quickly modify its inventory in response to shifting fashion trends shows how important it is for a supply chain to be responsive in the face of demand fluctuations (Ferdows et al., 2004). By cutting lead times and raising customer satisfaction, the incorporation of AI technology can further optimize supply chain operations (Sanders, 2016). Global trends, like changes in the manufacturing sector, also call for flexible supply chains to handle difficulties brought on by trade disputes and unstable economies (Bowersox et al., 2019).

An effective and flexible supply chain is essential for companies. The effective logistics provided by this supply chain guarantee prompt delivery, cost containment, and customer satisfaction.

First, on-time delivery is guaranteed by an effective supply chain. According to Mangla et al. (2018), prompt delivery is the cornerstone of trust and enduring collaboration between businesses and consumers. Businesses can react swiftly to client demands and provide goods or services on schedule by streamlining procedures and information distribution in the supply chain (Wallace, 2020).In addition to satisfying consumer wants and raising customer happiness, this helps businesses build a solid reputation and remain competitive in the market.

Second, expenses may be successfully managed via an efficient supply chain. Costs may rise as a result of supply chain waste and delays (Agrawal et al., 2021). Businesses may save logistics expenses, inventory overhang, and warehouse operating costs by improving transportation logistics, inventory control, and warehousing layout. Furthermore, a well-functioning supply chain may also lessen issues like returns and defective goods, which helps businesses save money on both quality and after-sale services (Homrich et al., 2018). Businesses may boost competitiveness, increase profit margins, and provide the groundwork for long-term, sustainable business growth by controlling costs.

And last, satisfied customers are a result of an effective supply chain. When customers use services or make purchases of goods, they anticipate a positive interaction and high-quality care. Businesses may fulfill consumer expectations and increase customer satisfaction by offering services like flexible and quick after-sales assistance, correct order processing, and timely delivery through an effective supply chain. A higher level of customer satisfaction will aid in gaining new clients, keeping hold of current ones, and growing market share.

An effective and flexible supply chain is critical to enterprises. It provides substantial support for the competitiveness and sustainable growth of the firm by ensuring timely delivery, controlling expenses, and increasing customer satisfaction (Kane et al., 2018). Businesses should actively devote time, money, and resources to enhancing the supply chain's overall effectiveness. This may be done by improving the management of supply chains to adjust to shifting market conditions and to continuously innovate and develop in order to gain a sustained competitive edge.

C. The Impact of Additive Manufacturing on the supply chain

According to market demand, as 3D printers become more affordable and the public's acceptance of them grows, home 3D printing will undoubtedly become more popular and the need for 3D printing supplies will rise. The need for 3D printing consumables will rise dramatically in the industrial sector as large-scale 3D printing becomes more feasible in the future. Meanwhile, from the standpoint of the material field, as 3D printing technology continues to gain popularity, the current steel, chemical fiber, and ceramics A sizeable amount of the operations of upstream bulk material extraction businesses, such those that generate gypsum, cement, and stone, will go toward manufacturing the many consumables needed for 3D printing. In conclusion, the distribution and storage of raw materials for 3D printing will undoubtedly make the logistics sector a significant new business area in the future. In its "3D Printing Raw Materials 2014-2025: Situation, Opportunities and Forecasts" report, renowned research firm IDTechEx (2013) noted that, prior to 2015, the output value of 3D printing raw materials, such as metals and plastics, will rise to as much as 244 million US dollars before 2025. The market for 3D printing materials is expected to generate an output value above US$615 million, further demonstrating the logistics sector's ability to support the growth of 3D raw material-related enterprises.

1. Logistics operations are more streamlined and efficient, and transportation expenses are decreased.

In the fast-paced world of today, logistics is essential to a company's success. Various operations must be managed in the complex supply chain process. Logistics operations were previously handled manually, which resulted in numerous errors and inefficiencies. But as technology has advanced, logistics processes have become more streamlined, economical, and efficient. One such technological advancement that has revolutionized the logistics sector is the implementation of Order Management Systems

(OMS).

An order fulfillment process can be managed and streamlined with the help of an order management system (OMS). From the time an order is placed until it is delivered to the customer, it offers complete transparency across the entire chain process (Baron, 2021). OMS makes sure that every step of the process is automated, which lowers the possibility of mistakes and boosts productivity. Businesses can also decrease order fulfillment times, prevent stockouts, and manage inventory more effectively by utilizing OMS (Fleming & Konstantaras, 2014).

Here are some key benefits of using OMS in logistics operations:

a. Streamlined Order Fulfillment: By automating the order fulfillment procedure, OMS helps to shorten order processing times. Consequently, this expedites delivery and elevates the clientele's experience. Businesses can track shipments, handle orders more effectively, and give customers real-time updates with OMS.

b. Enhanced Inventory Management: OMS gives companies access to real-time information about their stock levels. They are able to decrease order fulfillment times, prevent stockouts, and better manage their inventory as a result. In order to guarantee that they have the appropriate stock on hand when needed, OMS also assists businesses in forecasting their inventory needs.

c. Improved Customer Experience: By automating the entire order fulfillment process, OMS lowers the possibility of errors. Thus, the customer experience is improved. Businesses can track shipments, guarantee on-time order delivery, and give customers real-time updates with OMS.

d. Cost Savings: By automating the order fulfillment process, OMS assists companies in lowering their operating expenses. This lowers the possibility of mistakes, boosts productivity, and shortens the order fulfillment time. Consequently, this aids companies in cutting expenses and raising profits.

For businesses trying to increase the effectiveness of their logistical procedures, OMS is an essential tool. It offers complete transparency of the supply chain process, improves inventory control, raises customer satisfaction, and reduces expenses. In today's fast-paced world, OMS use has become more and more crucial, and companies that wish to stay ahead of the competition need to adopt this technology (Xu et al., 2018).

The major way that additive manufacturing has affected the supply chain for logistics is in how well-organized and effective the logistics process is. Businesses may save shipping costs by streamlining and optimizing logistics operations through the use of additive manufacturing technology.

Technology for additive manufacturing has the potential to simplify logistics. Purchasing raw materials from suppliers is a necessary step in the conventional manufacturing process, which also involves many stages of processing and assembly before packing and shipping are completed. This procedure is prone to part overstocking and frequently takes a lot of time and money. By directly creating things layer by layer using additive manufacturing technology, fewer intermediary storage and transportation linkages are needed, which saves time and money in the logistics process. Furthermore, on-demand production, production in accordance with the precise specifications of client orders, preventing needless inventory overruns, and further optimizing logistics operations are all made possible by additive manufacturing (YU XIAO, 2016).

Due to the product's volume and form restrictions, pieces must be delivered in batches during traditional manufacture, necessitating the need of extra packaging and protective techniques. This raises the expense of shipping as well as raising the possibility of product damage while being transported (Moore and Lucas, 2021). Products with a great degree of freedom and flexibility may be made by stacking layers using additive manufacturing technology. This implies that several components may be manufactured as a single unit, eliminating the requirement for protection and packing during travel and cutting down on the expense of shipping. Furthermore, local production may be made possible via additive manufacturing, which brings the process of production closer to the customer, eliminates the requirement for long-distance shipping, and lowers transportation expenses even more.

Streamlining and optimizing logistics processes is how additive manufacturing technology primarily affects the logistics supply chain. Businesses may minimize intermediate storage linkages and logistics links, optimize the logistics process, and increase the effectiveness of logistics operations by implementing additive manufacturing technology (Farooque et al., 2019). In addition, additive manufacturing may accomplish local production, cut down on the requirement for long-distance transportation, and lower shipping costs by reducing the need for packaging and protection. Because of these benefits, additive manufacturing is a valuable tool that businesses should consider implementing to enhance supply chain efficiency and cut expenses in their logistical operations.

2. Personalization and manufacture on demandreduction of warehouse and inventory requirements through on-demand production

As opposed to mass production, on-demand manufacturing, also known as manufacturing on demand (MOD), is a form of manufacturing in which products are only produced when needed. In contrast to centralized mass production, it refers to producing goods both physically and digitally closer to the point of consumption through flexible, distributed production systems.

Standardized, one-size-fits-all products were once considered acceptable, but modern consumers expect exact customization and versions made specifically for them, which cannot be produced in large quantities. Businesses need to respond to this demand for specialized variations with more agile, responsive production models if they want to stay competitive.

Businesses often need to create and store vast amounts of standardized items in the conventional manufacturing process, which necessitates expensive inventory and storage demands. Businesses also have to deal with issues like product expiry, limited storage space, and inventory backlogs as a result of the many product standards and styles. Nonetheless, these issues can be successfully resolved with the application of additive manufacturing technologies.

Additive manufacturing technology reduces inventory and warehousing costs by optimizing the logistics supply chain through customisation and on-demand production (Parks et al., 2020). Customized manufacturing lowers inventory costs and risks by avoiding overproduction and overstocking issues. Conversely, on-demand production minimizes the need for storage space and associated expenses by producing goods based on the actual need for the order. This can save operational expenses while simultaneously enhancing the effectiveness of logistics, reducing the duration of the supply chain, and improving the ability to adjust to shifts in consumer demand.

This need is met by on-demand systems, which allow for flexible, customized manufacturing in smaller quantities. Products can be swiftly modified to accommodate changing customer needs. This is a significant move away from high-volume manufacturing and toward flexible, low-volume production that is responsive to real-time consumption patterns.

Additive manufacturing technology may reduce the requirement for storage and inventory in the supply chain for logistics by personalized and immediately production(Shaheen et al., 2019). Tailored manufacturing addresses specific customer requirements while preventing overstocking. Production that is done on demand lowering expenses and the amount of storage space occupied in accordance with real order needs. Because of these benefits, additive manufacturing technology is a valuable tool for logistics supply chain optimization, enabling businesses to lower operational costs, increase productivity, and more effectively adapt to changes in consumer demand.

3. prospects for personalization and customization that increase customer satisfaction

Customizing a good, service, or experience to a customer's specific requirements and preferences is known as personalization. What makes customization so crucial for companies, then? Businesses in today's fast-paced, fiercely competitive market are constantly searching for methods to set themselves apart from the competition. Businesses can accomplish this through personalization, which enables them to give clients a unique experience that is catered to their requirements and preferences (Lindecrantz et al., 2020).

But differentiating yourself from the competition isn't the only goal. The financial line of a company can also be significantly impacted by personalization. Through establishing a more intimate and significant relationship with their clientele, companies can enhance customer satisfaction, boost sales, and foster customer loyalty. To put it briefly, personalization is an effective strategy that firms can use to draw in new clients, keep existing ones, and eventually expand (Team & Team, 2023).

The technique of additive manufacturing allows for product customization. The conventional manufacturing method mainly uses the massive amounts manufacturing method, which is difficult to suit the unique demands of consumers (Guevara, 2021). To accomplish personalized product manufacture, additive manufacturing may be used to develop and produce products that are specifically tailored to the needs of the consumer. This implies that clients can alter the product's dimensions, form, content, and even functionality to suit their demands (Garadis, 2023). Customers are more satisfied with items that are customized to their specific demands thanks to additive manufacturing, which allows for the creation of unique products.

The logistics supply chain benefits from more effective production procedures brought forth by additive manufacturing technology. In the conventional manufacturing mode, there are several production linkages and intermediary links, some of which may result in resource and time loss. With additive manufacturing, design data can be translated straight into tangible goods without the need for intermediary pieces like fixtures and molds. This substantially streamlines the production process, lowers waste, and boosts productivity. This lowers production costs and increases customer satisfaction by reducing lead times for products (Ray, Jason T., 2013).The logistics supply chain gains from additive manufacturing technology's more efficient production techniques. There are multiple production connections and intermediary links in the traditional manufacturing system, some of which may cause resource and time waste. Design data may be converted directly into actual items with additive manufacturing, negating the need for intermediate components like fixtures and molds. This significantly reduces waste, increases productivity, and simplifies the production process. By lowering product lead times, this decreases production costs and boosts customer satisfaction (Ray, Jason T., 2013).

4. Potential impact on traditional supply chain models and distribution networks

The employment of additive methods influences the customer's engagement in the design process and offers the possibility of having decentralized structures located near to the customers. Hence, according on their requirements, the qualities of the product they sell, and the market they service, businesses may decide how to incorporate additive technology into their SC in a centralized or decentralized manner (Holmström et al., 2010). In a centralized system, AM is used to develop items that are then sent to various distribution hubs from a single office. Although it doesn't shorten transit times, this approach allows demand to be combined from several places (Calignano & Mercurio, 2023). This guarantees that the capacity of the AM machine investment is used efficiently.The centralized strategy works well when lead time is not a critical factor and market demand is restricted.

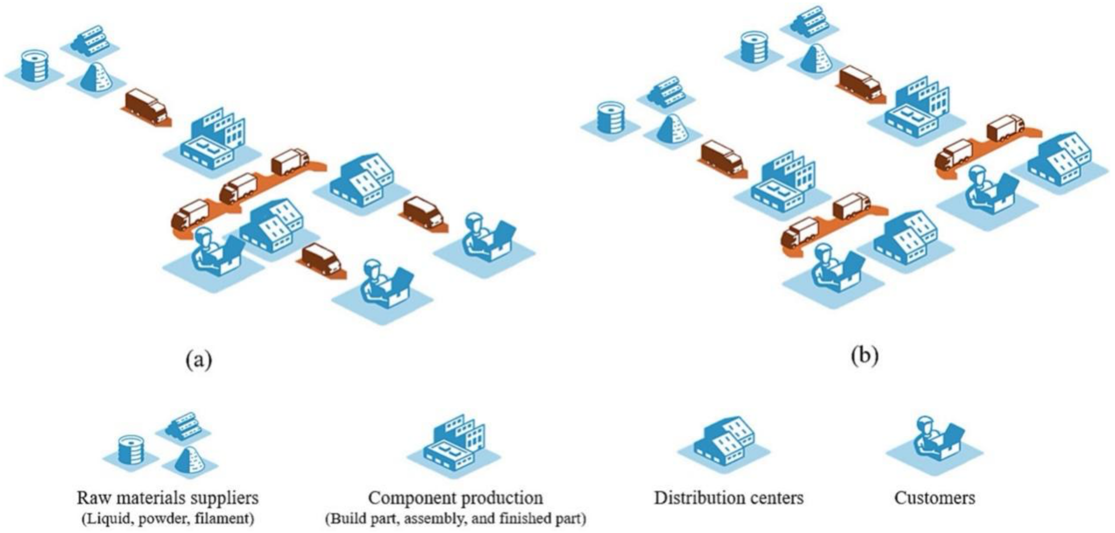


Figure 4-1 (a) Centralized and (b) distributed AM from Sciencedirect database

Distributed AM, on the other hand, enables production to take place in every distribution center, removing the need for storage, reducing transportation expenses, and speeding up response times. Barz et al. (2016) conducted a computational analysis on the impact of additive manufacturing on transportation costs. The application of technology and the reorganization of production locations, according to Barz et al. (2016), lowers transportation costs, with minimum reductions of 43% and maximum reductions of 58%. Moreover, a supply chain is less vulnerable to shocks and disruptions when a small number of commodities are produced across multiple facilities; the effects are centered in a particular employment location rather than being widespread or regional.in a single location of employment rather than being widespread or regional. Furthermore, decentralized production enables businesses to investigate the various markets where their production and distribution hubs are situated and modify their output accordingly. Its implementation, however, necessitates large expenditures for 3D equipment and specialized labor, which are only warranted in extreme circumstances.

In general, the three main levels of the SC are upstream, midstream, and downstream. Suppliers and manufacturers of spare parts and raw materials are located upstream; transportation and warehousing operations are located midstream; Downstream includes retailers and the delivery of finished components to end users..

Suppliers, producers, wholesalers, retailers, and consumers are connected between these levels via five sorts of flows: product flows, process flows, information flows, money flows, and energy and natural resource flows. Figure 4-1 shows a decentralized network reconfiguration model, a centralized AM model, and a standard SC that account for these fluxes. In a traditional manufacturing setup, the supply chain comprises multiple stakeholders, ranging from the suppliers of materials and components to the end users.

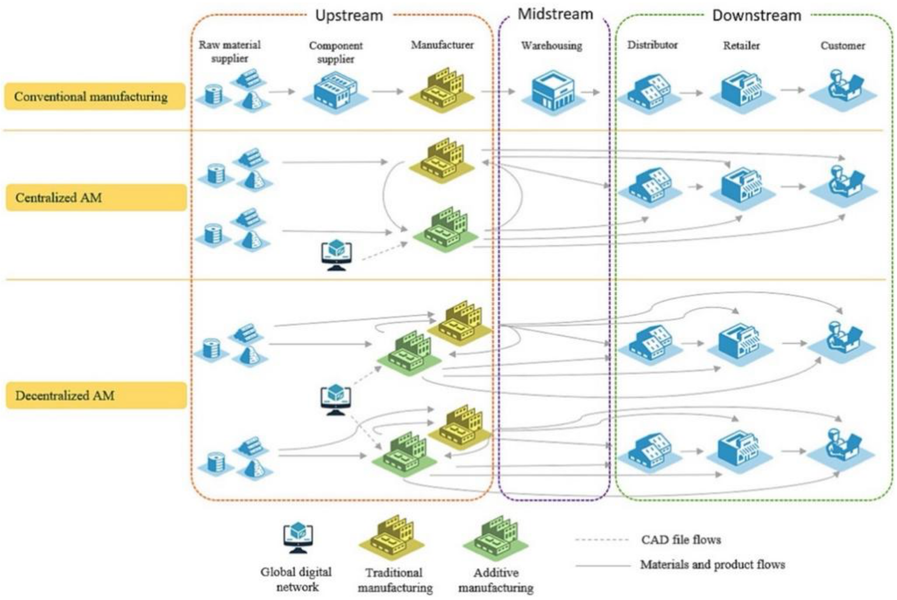


Figure 4-2 Supply Chain reconfiguration from Sciencedirect data base

In recent years, there has been a considerable advancement and implementation of additive manufacturing technology, which is a manufacturing method that constructs three-dimensional items by adding materials layer by layer. The logistics supply chain is being significantly impacted by this new technology, which is also potentially affecting the distribution network in addition to altering the conventional supply chain paradigm.

The production process is where additive manufacturing technology most affects the conventional supply chain paradigm. While additive manufacturing technology allows for customized production in response to demand, it also eliminates the inventory and waste issues associated with traditional production. Traditional supply chains are based on large-scale mass production and centralized storage structures.

Additive manufacturing minimizes the need for physical prototypes, significantly decreases the time needed for product development, and boosts production efficiency by building items directly from digital models. Furthermore, the flexibility and manufacturability of additive manufacturing allow businesses to better adapt to the quick changes and wide range of market demands.

The traditional supply chain paradigm is most impacted by additive manufacturing technologies in the production process. In addition to enabling customised production in accordance with demand, additive manufacturing technology does away with the waste and inventory problems that come with conventional production. Conventional supply chains rely on centralized storage facilities and large-scale mass production. By creating products directly from digital models, additive manufacturing reduces the demand for physical prototypes, shortens the time required for creation of products, and increases production efficiency. Furthermore, firms are better able to adjust to the rapid changes and diverse range of market needs due to the adaptability and manufacture of additive manufacturing..

In the production process, additive manufacturing technologies have the biggest influence on the conventional supply chain paradigm. Not only can additive manufacturing technology meet demand by customizing output, but it also eliminates waste and inventory issues associated with traditional manufacturing. Conventional supply networks depend on massive mass manufacturing and centralized storage facilities. Additive manufacturing decreases the need for physical prototypes, speeds up product creation, and boosts production efficiency by producing goods directly from digital models. Additionally, because additive manufacturing is so flexible, businesses can better react to the wide range of market demands and quick changes.

5. Faster response times and improved flexibility

Thanks to contemporary ICT, the smart supply chain might be more flexible than the old supply chain. There are several approaches to implementing an intelligent supply chain. Conventional industrial facilities outfitted with intelligent software systems can be a part of a smart supply chain. Anticipatory shipping methods enable a business to meet the needs of each unique customer. The flexibility that linked smart factories with additive manufacturing may attain and share through a cloud system is the main topic of this article. The flexibilities were found through a survey of the literature and are divided into six groups. Please take note that the aim of this article is to find intelligent supply chain adaptability using additive manufacturing and other swappable methods, rather than to do a complete analysis of the literature on smart supply chains.

a) Design Flexibility

Using basic elements like metal, ceramic, and polymers, an additive manufacturing AM produces layers (Wong &Hernandez, 2012). There is an enormous variety of product forms available since AM can produce objects in the required shape without the requirement for molds once the raw ingredients required for production are available. Flexibility in design pertains to the ability to create a product with multiple different designs. It is possible to create bespoke products with different designs fulfilling the same purpose using AM (Kiritsis & May, 2019).

AM eliminates the need for costly tools required in subtractive manufacturing techniques like drilling, grinding, and casting and allows production to be based on CAD models (Berman, 2012). Product design has a great deal of latitude and is not as restricted by production procedures. Hollow-core constructions are simple to create with 3D printers while preserving or improving product features and performance. For instance, Lu et al. (2014) suggest a honeycomb-cell construction that uses the least amount of material while offering strength in stress. Qin and colleagues (Qin & Compton, 2015) examine the characteristics of spider web design. Through topology optimization, these novel design types enable manufacturers to produce products that fulfill the same purpose as solid type designs while weighing less in the parts (Beyer & Zegard ,2016). Additionally, a producer can reduce raw material costs by using fewer raw materials to manufacture lighter parts. Lighter items are very appealing to the automotive and aviation industries since they use less energy and emit less CO2.

b) Product Flexibility

Product flexibility is the capacity to produce several commodities in a same facility or supply chain in response to changing market demands. This concept is closely related to mass customization, despite some notable differences (Da Silveria et al., 2001). Unlike a typical large-scale customization system, which is based on a modular structure or product postponement (Berman, 2002), massive customization in the intelligent supply chain is based on CPS and the Web of Things and Services in the manufacturing system (Da Silveria et al., 2001). Moreover, unlike traditional systems, it does not require a high degree of supply chain integration (Berman, 2012).

Additionally, additive manufacturing are crucial in fulfilling the specific needs of each client. Historically, the primary application of the AM process was the low-cost fabrication of prototypes and mockups. Nonetheless, the use of AM is growing as a result of technological advancements and dissemination. Companies can use modest amounts of completed items in a range of sizes, colors, and functionalities to assess consumer response instead of relying just on one product. Furthermore, customized end items with unique product designs can be effectively produced using additive manufacturing without the need for retooling (Campbell et al, 2011). Therefore, the greatest advantage of additive manufacturing is its capacity to produce small quantities of various objects in a flexible manner without incurring incidental tooling costs (Bassoli et al., 2007). If all of the raw ingredients needed to print the items are the same, any product might be made in a factory..

c) Process Flexibility

A manufacturing site's process level has to be adaptable enough to handle a variety of modifications in order to make customized items (Khan & Turowski, 2016). The capacity to manufacture a product utilizing a variety of production procedures is referred to as process flexibility.

Process flexibility can be achieved with the using 3D printers on the production line, allowing for the manufacturing of a same product in multiple ways. Put differently, producers have the flexibility to choose the most effective technique for producing a certain product based on the tools or resources that are at their disposal. Initially, the product can be altered to produce finished items with fewer components., necessitating fewer assembly steps (Cotteleer & Joyce,2014). For instance, GE Aviation used to assemble 20 pieces to create fuel nozzles. These days, they use additive manufacturing to create them as single units. Second, the choice of manufacturing procedure may also be influenced by the performance of 3D printers. A tiny 3D printer, for instance, produces the product's component pieces, which are then assembled., whereas a big 3D printer produces one thing at a time.. Thirdly, the choice of material affects the manufacturing process. Metals typically need post-processing, but polymers usually only need a minimum finishing step (Petrick &Simpson,2013).

d) Supply Chain Flexibility

The implementation of a new supply chain model may be necessary as a result of technological advancements that alter the structure of the chain. Supply chain flexibility refers to the shared and adaptable operation of facilities within the networked smart factories. In the context of smart factories, real-time data collection, dynamic cooperation amongst intelligent agents, and manufacturing outsourcing—which has been made simpler by the use of AM—can all lead to supply chain flexibility. Furthermore, in a collaborative network, firms share demand and capacity through the use of cyber-supported collaboration infrastructure, which is crucial.

Furthermore, there is a great deal of uncertainty due to the wide range of items that come from customizing. By sharing the capacity of the network's facilities, it is feasible to adaptably handle such significant supply chain uncertainty (Hsieh et al 2008). Experts believe that collaborative manufacturing is a new business model that makes use of cutting-edge technologies. When a factory's capacity for a certain process is limited, products can be produced by sharing machines and processes with other companies in the network. In other words, the capacity utilization of the network's factories may be maximized and the supply chain network's available resources can be employed effectively.

6. Enhanced product design and innovation

The use of additive manufacturing (AM) has become more attractive due to advancements in techniques, technologies, and applications such as Biological printing, Four-dimensional (4D) printing, Nanoscale printing, and Metamaterial printing (Dogan et al., 2020).

Since 2013, 4D printing has become more popular in academic and business circles as one of the most current developments in additive manufacturing (AM) technology; nevertheless, additional research and development is still required before it can be commercialized (Teng & Zhang, 2020). Because created things may now be altered to take on complex structures by changing their size, shape, functioning, and other qualities, 4D printing is a subset of 3D printing that goes above 3D printing. According to Chu, H. et al. (2020), this process is called the formation of a complex organic structure that varies over time and purposefully reacts to outside stimuli. These techniques have been used to flexible robots, tissue engineering, and grippers.

Several studies highlight the growing body of understanding regarding intelligent materials, available stimuli, mathematical modeling, geometric programming, and AM technologies that will require further research on computer-aided design software for illustrating the characteristics of smart materials in conjunction with physical simulation at multiple scales. Once more, this proposes merging AM with AR. However, in order to guarantee the quality of the parts, new measuring tools or other forms of measurement must be developed. Additionally, manufacturing processes must be sufficiently reliable to ensure that the appropriate and repeatable spacing between the voxels representing the materials is maintained (Pei, E.; Loh, G.H, 2018). Since AM technology has been integrated into production processes, businesses have observed a rise in adaptability and speed when it comes to changing production sites and timetables. This has reduced operational expenses by improving the usage of raw materials and resources. This technology also helps manufacturers become more competitive by cutting down on the amount of time needed for product design and manufacturing as well as the time it takes to deliver the finished product to the customer.

According to the literature, there are seven possible effects of AM on SCs (Ben-Ner et al 2017):

- Effect 1: Reduced complexity in the supply chain: AM technology often eliminates the requirement for numerous component assembly by producing the full item. It also shortens the manufacturing flow, enabling better monitoring of the materials utilized, and saves internal production expenses (such as labor and internal transportation).
- Effect 2: Flexible inventory management and logistics: Since manufacturing can occur close to the point of final consumption, the incorporation of AM technology can have a significant impact on transportation and logistics operations as well as global value chains. This can save expenses for a number of things, such as inventory, spare parts, configuration and reprocessing, and other related expenses like transportation. It looks like a new trend in manufacturing is coming that focuses on substituting digital stock kept in a 3D file format for tangible goods and raw material stock.
- Effect 3: Mass customization: Rather than mass-produced goods, additive manufacturing (AM) has promoted mass (production) customization because it allows for the environmentally conscious, reasonably priced production of tailored products with flexible designs.
- Effect 4: The decentralization of manufacturing: On-site production and consumption are only one of the ways additive manufacturing (AM) technology might enhance global supply chains. This can shorten the entire time to market and hasten the reaction to changes in customer demand.
- Effect 5: Design freedom and rapid prototyping: AM technology allows components with complex geometries to be produced, circumventing some of the drawbacks of classic subtractive methods, such as greater prices.
- This technique is associated with a new age in global production brought about by the digitalization of manufacturing, wherein a wide range of essentially diverse

things may be created swiftly and easily in compliance with end customers' demands.

- Effect 6: Ecological and resource-efficient: Additive manufacturing (AM) techniques often consume less energy than conventional production techniques. However, through remanufacturing, reconditioning, and repair, shorter, more cooperative supply chains can increase a product's lifespan.
- Effect 7: Discussions about laws, security, and safety There is currently no legislation governing AM or 3D printing that governs the digitalization of tangible goods.

Therefore, there is currently insufficient oversight or regulation of the widespread use of digital files that contain actual scanned products. Moreover, considering the variety of products that may be 3D printed, safety and intellectual property rights policies and standards are essential.

Unlike traditional manufacturing methods, additive manufacturing (AM) is better suited for tasks requiring a higher degree of customization or complexity. However, given current cost models, some businesses may still find that using traditional manufacturing techniques is more appropriate for large production volumes. Compared to traditional manufacturing machines, AM machines are significantly more expensive to purchase, despite the fact that they offer greater production flexibility (Pereira, T.; Kennedy, J.V,2019).

When the material is powdered, there is an additional health and safety concern that necessitates meticulous design optimization to figure out how to extract the powdery residues. Dust accumulation inside a component affects not only its mechanical and structural integrity but also its health and safety (Diegel, O.; Singamneni, S,2010). Complex quality standards and criteria have resulted from changes in the production process and a wide range of materials, which pose problems with precision, reliability, and quality assurance. (Newman, S.T.; Zhu, Z,2015). In order for AM to eventually gain traction in the commercial market, it will be necessary to make investments in continuous certification, online quality control procedures, a database containing AM material properties, high process stability, and design guidelines (Pereira, T.; Kennedy,2019).

Testimonies were collected in 2019 as part of a project sponsored by the European Regional Development Fund (Grant Number: POCI-02-0853-FEDER-000041) from Portuguese metalworking enterprises that had adopted AM technology. 2019 saw the completion of the research. One of the cutlery manufacturers evaluated and validated prototypes using additive manufacturing (AM) technology after working with their clients on designs (Araújo, N., 2017). "The creative and production process was able to introduce significant improvements in the design and manufacture of some components, primarily through the use of additive manufacturing technology (3D printing)," asserted a different medical equipment company.Concept studies were specifically utilized in their manufacture to direct component application and testing, as well as the development of a digital interface for specific devices. By using 3D printing to create prototypes, the manufacturing process's increased iterations sped up time to market and, as a result, decreased manufacturing risks and problems throughout the whole production cycle. To summarize, the implementation of additive manufacturing (AM) technology resulted in cost savings, setup times, and transformation times, as well as internal improvements through component redesign and creation. In order to better prepare for the future of customized digital production, it also prompted the company to reevaluate its storage and logistics procedures as well as its production process.

Additive manufacturing (AM) technology has the potential to totally change a number of strategically important industrial industries because it offers unrivaled flexibility in product design, production, and delivery.

7. Environmental sustainability and waste reduction

Nearly 350 million tons of plastic were produced worldwide in 2017, making it the largest market regarding crude oil. (Plastic Europe, 2019). Most polymers and plastics currently in use are derived from non-biodegradable petrochemical materials, however, given that these resources will ultimately run out, is not a sustainable solution. Additionally, the production of these materials and their incineration during disposal release greenhouse gases into the atmosphere, endangering global warming. Furthermore, in more recent times, people have become aware of the pollution that plastics cause in soils (Chae and An, 2018) and particularly in oceans (Ostle et al., 2019). Reducing the amount of material disposed of in landfills and the quantity of raw resources consumed requires recycling. The direct application of post-consumer polymers is the most efficient method for managing plastic trash. (Chen et al., 2011).

These issues are well known to researchers, as evidenced by the exponential growth in published work assessing the effectiveness of recycled materials (Lanzotti et al, 2019) and employing eco-friendly manufacturing methods and technologies (Piedade et al., 2020). This knowledge can greatly aid in lowering the issues, as can the application of technologies like additive manufacturing that generate little to no waste. Moreover, using a variety of materials in polymer 3D printing might reduce the amount of radiation and hazardous chemicals needed to create products with the right chemistry. (Piedade et al., 1995). Even in their final stages of life, plastics are valuable resources. In 2016, 31.1% of the garbage collected in Norway and Switzerland was disposed of through recycling, 41.6% through energy recovery, and 27.3% through landfilling..

Furthermore, recycling of plastic trash surpassed landfilling of the garbage for the first time. Between 2006 and 2016, the volume of plastic garbage collected for recycling increased by about 80% (PlasticEurope, 2019). It's time to start using recycled materials in usable pieces instead of just plastic bags because the numbers are promising. 4. In the field of polymer processing, 3D printing has become the go-to method for creating functional parts for a range of applications, such as agriculture, food production, biological, unmanned aerial cars (UAVs), biological printing, membrane that's filled (selective barriers) technology, aviation, civil engineering, matrix metal composites, and bioprinting.

Furthermore, 3D printing—which is regarded as a clean processing technology—can definitely leverage the circular economy as a tool rather than a means to an end in order to significantly address the global problem of plastic contamination by producing new components or parts using post-consumer recycled polymers. The most extensively documented polymers utilized in fused deposition melting (FDM) are Acrylonitrile–Butadiene Styrene (ABS) copolymer and Poly (lactic acid) polymer. Nevertheless, there hasn't been much written about their use as recycled filaments, especially when it comes to their post-consumer use as a raw material at the end of a life cycle. These materials can be recycled, which may lead to certain issues.

The benefits of additive manufacturing (AM) may be seen at several stages of the life cycle of a product or material, according to Despeisse and Ford (2015) (Fig. 4-4). By increasing their functionality, things may be redesigned using AM. The CAD model allows the product's exact parameters to be altered based on its intended application. According to Ford and Despeisse (2016), the novel structures incorporated into the components have improved properties such as corrosion resistance, energy efficiency, and increased strength and stiffness.

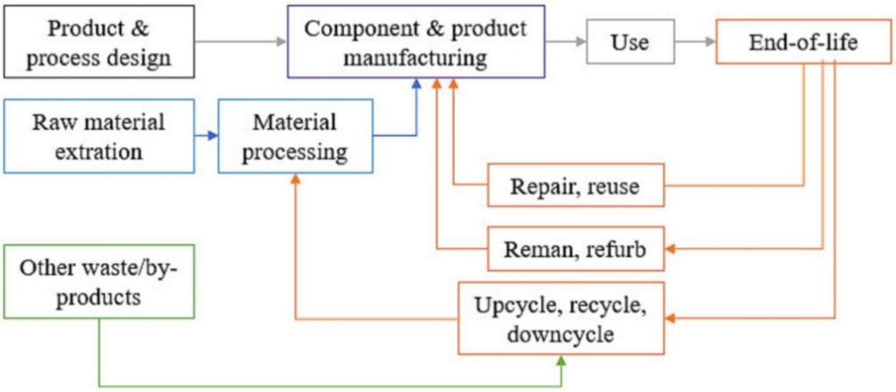


Figure 4-4 Different stages of the product and material life cycle from Sciencedirect database

Additionally, efficient design can lower a piece's weight by 35 to 65% (Villamil et al., 2018). This alternative is especially advantageous when a part needs to be built in a transportation system since it is lighter, which means using less fuel and producing less CO2 (Ingarao and Priarone, 2020).

One of the sectors most benefited by additive technology is aerospace. The excessive material waste that occurs during traditional production processes is a major contributing factor to the adverse environmental effects of producing aircraft components. The industry's expenses are impacted by the elevated ratio of buy to fly, which also exacerbates issues with environmental sustainability. Recent years have seen a significant decrease in these issues thanks to AM-enabled product redesign. The nozzle printing for LEAP jet engines at GE's Alabama facility, which reduced weight by 25%, led to a 20% decrease in fuel consumption and a 10% boost in power (Ghobadian et al., 2020). This is a noteworthy instance.

Additionally, the creation of simpler goods requiring fewer components and resources might be made possible by the redesign; this would allow for a reduction in material flows and, thus, a decrease in the environmental effect across the SC.

The incorporation of additive manufacturing (AM) can yield benefits beyond product design and potentially enhance the manufacturing process's design. The incorporation of additively manufactured components (such as tools and molds) can boost the effectiveness of the production process in terms of energy and resource utilization. Salcomp, a Finish company that leads the world in producing power supplies and electrical sockets for mobile phones, is one example. Operating in a high-volume industry, Salcomp's competitive advantage is primarily derived from cost and efficiency considerations. The corporation found that the period of cooling throughout the injection molding method was one of the problems preventing its Chennai factory from reaching its production efficiency targets. As a result, a collaboration was established with EOS GmbH, a German enterprise that creates laser-based powder bed fusion devices for metal and polymer applications. Salcomp engineers were able to rethink the molds' ventilation structure—which is utilized during production—in order to accelerate the dissipation of heat as a result of the collaboration. Then, utilizing laser powder bed fusion technology, these molds were created. The redesign's primary advantage was its ability to increase monthly production from 56,000 units to 8 seconds of cooling time. Reject rates decreased from 2 to 1.4%, resulting in an improvement in quality as a secondary benefit (Ford and Despeisse, 2016, Salcom and EOS GmBH, 2014).

3. Challenges

A. Supply chain integration and collaboration challenges

Collaboration in the supply chain pertains to reciprocal and shared processes among the involved parties, with the aim of establishing shared visions and mutual understanding, as well as resource sharing to achieve collective objectives (Flankegard et al., 2021). In order to enhance businesses' ability to manage internal and external operations successfully and meet supply chain goals, it comprises intentional synergistic relationships between them (Acquah et al., 2021). The goal of supply chain cooperation is to integrate an organization's operations and plans with those of its partner organizations in the network. As a result, it spans a range of horizons, including pricing and innovation, and requires the focus of several parties, such as suppliers, focal companies, logistics companies, retailers, customers, governments, and the public. (Song et al., 2017). Supply chain participants can gain a great deal from collaboration, which can improve the performance of supply chains. Collaboration can be used, for example, to redesign workflows and encourage resource sharing among supply chain participants in order to improve performance. Moreover, supply chain participants' resources and competencies—which arise from cooperation—now serve as the primary sources of long-term core competitive advantage (Chauhan et al., 2022). Moreover, achieving the intended strategic goals in supply chain networks requires risk- and benefit-sharing, which is only possible when partners collaborate on tasks such as scheduling and designing products, exchange of information, and knowledge sharing, among other things (Chauhan et al., 2022, Van Hille et al., 2020). Information and communication technology (ICT) can thereby facilitate collaborative activities between actors/partners in a supply chain network, such as companies and logistics service providers (Wijewickrama et al., 2021).

Similarly, in order to enable the implementation of Industry 4.0 innovations like additive manufacturing, Businesses must collaborate with supply chain partners to collaboratively create digital solutions. (Rocha et al., 2022). The main obstacles to digital innovation, especially for manufacturing firms, are supply chain cooperation issues involving the broadest possible variety of organizational partners/actors. For instance, collaborating throughout the supply chain can facilitate the implementation of additive manufacturing, which presents an opportunity to balance resilience and efficiency at the supply chain level and establish ambidextrous dynamic capabilities (Belhadi et al., 2022). Additionally, additive manufacturing has a significant impact on supply chain decentralization, manufacturing networks, logistics effectiveness, and supplier collaboration (Barata, 2021). Nonetheless, industry 4.0 technologies might assist manufacturing supply chains in forming alliances that enable them to dynamically pool production capacities in order to jointly take advantage of new business prospects (Cisneros-Cabrera et al., 2021). Supply chain collaboration leverages the sociability and usability qualities of digital technology to allow partnering that offers competitive solutions. It is driven by business, supply chain, and technical advances that place pressure and uncertainty on partnering enterprises (Rocha et al., 2022).

B. Technological limitations and infrastructure requirements

Additive manufacturing, commonly known as 3D printing, has been rapidly adopted by numerous industries due to its numerous advantages, which include customization, faster production times, and reduced overall prices (Sargent Jf ,Schwarts RX,2020). However, there are challenges involved in implementing 3D printing. Based on the current body of research, there are numerous barriers that keep 3D printing from becoming widely adopted. The requirement for integrated safety technology is a major barrier. As with any new technology, safety measures should be taken into account, and 3D printers are no different (Yi H,2022). Data architecture becomes more challenging because 3D printing requires complex software and systems for both design and manufacturing (Hossian Ma et. al 2022). Other factors that make 3D printing more challenging are the need for continuous monitoring and adequate lighting for effective operation. Along with the difficulty of mass-producing 3D-printed things, another major obstacle to the widespread application of this technology is the high cost of the necessary equipment (Ter haar B et. al 2023). Smaller companies may find the cost of integrating this technology to be prohibitive, particularly if it requires a change in operating procedures (Al Tartoor Y et. al 2020). Furthermore, the potential of 3D printing technology may be constrained by the narrow scope of software creation and capabilities, as well as the constrained degree of technical implementation (Luhar S,Luhar I, 2020). Smaller companies may find the cost of integrating this technology to be prohibitive, particularly if it requires a change in operating procedures . Furthermore, the limited scope of software development and capabilities, as well as the restricted extent of technological implementation, may limit the potential of 3D printing technology (Hamidi F,Aslani F, 2019).

Data privacy concerns and a lack of service providers are major barriers to the widespread adoption of 3D printing (Sakin M, Kiroglu YC, 2020). Among the factors contributing to the challenges are regulatory and legal obstacles, an inadequate administrative framework, and the absence of independent evidence regarding the capabilities of additive manufacturing (Bos F, Wolfs R, 2016). The workforce's and workers' lack of knowledge and training is another significant obstacle to the successful use of 3D printing technology (Rehman AU et. al 2023). Numerous major problems prevent the widespread use of 3D printing technology, including inadequate onsite data collection, variation in data, longer production schedules, problems with trust management, reduced effectiveness, restricted recycling capacity, and a shortage of inside additive manufacturing abilities (Singh R et al., 2021). Before 3D printing is widely used, a number of challenges have been noted in the literature (Wang Q et. al 2018). To overcome these challenges, innovative software and systems development, reduced manufacturing and equipment costs, enhanced data administration and acquisition, and improved safety protocols are all essential (Waqar A et. al 2023). Many of the obstacles hindering the widespread use of 3D printing technology might be removed by appropriate legislation and regulations.Last but not least, the effective use of 3D printing technology depends on resolving the workforce's and workers' lack of knowledge and training.

AM's issues have sparked cross-disciplinary initiatives to discover, model, and manage significant process-structure-property connections for quality enhancement. As a result, there is a lot of ongoing research being done in the fields of Design Theroy,Materials informatics, , Process and Measurement science, Systems engineering, Numerical or Analytical modeling, and software and hardware development in AM. Data-driven approaches have gained popularity among the currently available solutions for AM problems because they provide special advantages over analytical or numerical approaches. Researchers have employed Various Machine Learning (ML) and Deep Learning (DL) models to address AM challenges by utilizing data on Design, Material, Process, Structure, and Properties (Qin et al., 2022). The many reviews of data-driven AM applications that are currently available highlight the different aspects of machine learning applications in AM, such as non-destructive testing (Charalampous et al., 2020), ML architectures (Qi et al., 2019), AM data types (Zhang et al., 2022), physics-informed ML (Mozaffar et al., 2021), and research opportunities (Qin et al., 2022).

The industry appears to be on the verge of adopting ML-assisted AM solutions as they demonstrate success in the lab.To create, put into practice, oversee, run, and maintain AM's machine learning models, the industrial implementations of these solutions need to consider them from a systems perspective. Despite the fact that AM informatics has previously considered the systems engineering perspective at the data (Kim et al., 2015) and information (Mies et al., 2016, Bonnard et al., 2019) levels, there is no reference on managing ML models at the industrial scale. The majority of AM initiatives concentrate on implementing stand-alone models in open loop or simple closed-loop scenarios without requiring a platform for model management (Phua et al., 2022). Similar endeavors center on the creation of AM systems for managing data (Liu et al., 2020). The majority of current initiatives only pay attention to the data and information's upstream components on the information, knowledge, wisdom, and data continuum.

Machine Learning Operations is a paradigm that allows ML models to be managed and deployed at scale (MLOps). MLOps are a set of best practices for developing, implementing, overseeing, regulating, and refining machine learning models, according to Kreuzberger et al. (2022). These features are systematically offered in an integrated environment by an MLOps platform. Although the production and operation ML practices can aid in the management of AM ML solutions, there are currently no standards to combine the two sides onto a single platform of that kind. Furthermore, up to now, no study has examined the systems-level management of machine learning models developed for AM operations. In this study, we define critical positions methods, systems, activities, and interactions as functional components in order to develop techniques that may be leveraged to establish an MLOps framework for generic AM process needs.

C. Impact on workforce and skill requirements

Computer Aided Design (CAD)

CAD serves as the basis for additive manufacturing(AM) because it allows you to create or duplicate your geometric form using the output of 3D modeling software.

Designing, adjusting, or enhancing an already-existing 3D model is one of the most important AM skills for this reason: spatial object design. A competent CAD designer's creativity and knowledge are difficult to duplicate (Ricoh USA, n.d.2020)

Even though CAD design software is now more widely available and easy to use, users still need to be proficient in the following areas:

i. Design thinkings
ii. Computational modeling
iii. Analysis
iv. Engineering

For aspiring operators, The acquisition of CAD skills might provide the greatest challenge among AM skill sets because to the wide range of varied competences needed.

Design for Additive Manufacturing, or DfAM, is a concept in design principles.

To manufacture (or print) items, AM builds materials onto CAD models layer by layer. Unlike most traditional manufacturing procedures, which entail adding or removing material to generate the desired shape—often while changing the shape to best support machine mass production—this method adopts a radically different approach.

AM releases designers from the mindset of mass production. Complex geometries and higher levels of customization are made possible by the layer-based additive nature. These give you the freedom to incorporate features into intricate parts without requiring the kind of simplification that is necessary for the majority of traditional mass production techniques.

Because of this flexibility and freedom, working in AM allows designers to think conceptually in very different ways, giving designers more of a chance to work with a "blank slate."

Nevertheless, AM still has its own factors to take into account when choosing which materials to use, how to support or build a project, or which process to employ. Finding and utilizing the tools (generative design, topology optimization, consolidation, or lattice structures) that best maximize the advantages of the additive process is the most crucial part of designing for additive manufacturing (AM).

Finishing

Creating a project and getting it ready for 3D printing are just two aspects of additive manufacturing. The degree of post-processing expertise required to create accurate and realistic model representations is a characteristic that sets professionals apart:

- Removal of supports
- Grinding
- Sanding

- Cutting
- Filling
- Painting
- Coating
- Polishing

Compared to conventionally machined components, 3D printed manufacturing parts provide various finishing issues, which makes finishing all the more important. Certain machines' layered 3D printing techniques might not be as precise as some conventional production techniques. Because of this, traditional computer numerical control (CNC) machining may still be necessary for the process of 3D finishing. The high level of dimensional precision required for manufacturing items may be obtained with CNC machining.

In the end, the material and finishing technique used for 3D printed items depend on the needs of their purpose (prototype, display model, or functioning parts). Comprehending and perfecting the diverse post-processing finishing techniques is imperative in order to achieve the intended result of the part design.

Safety

For those working in additive manufacturing, it is essential to comprehend the properties of materials, handle materials properly, and operate equipment safely. It's imperative to have an extensive knowledge base covering the safe operation and maintenance of downstream machinery and your 3D printers.

One part of AM production that is frequently disregarded is materials management, which includes disposing of any environmental waste. This information is particularly important for the metal additive industry, as there are extra safety and environmental factors to take into account. Particular training is required for:

- Personal protective equipment (PPE)
- Safety from fire
- Appropriate waste management techniques

The reverse engineering method

The potential to use 3D printing for inventory of old or replacement parts is an alluring feature that is driving the adoption of AM for many companies. In order to incorporate any part improvements made possible by AM and to replicate legacy parts directly, a significant amount of reverse engineering might be necessary. Difficult geometries are captured by high-resolution 3D laser scans and tight tolerances, necessitating testing and quality assurance prior to production.

Furthermore, not each redesigned part would be a suitable fit for additive manufacturing. Knowing the principles and limitations of additive manufacturing (AM) together with other manufacturing methods, an experienced designer may choose the optimal alternative, or even a combination manufacturing method that combines traditional machining with the complex geometries of AM.

Critical thinking and soft skills

Ultimately, even though practical technical skills are always prioritized, it is important to recognize that critical thinking and problem-solving abilities are a important part of the manufacturing process as a whole. Similarly, the importance of soft skills like leadership, teamwork, and communication cannot be overstated for your AM workforce of now or tomorrow. The greatest ambassadors for AM are your employees, but in order to effectively promote its wider usage and adoption, they must be able to clearly communicate its benefits to upper management.

Though AM is still in its infancy and has not yet achieved full industrial adoption or realized its full potential,it is about to have a big effect on the industrial industry. Finding a qualified workforce to manage it all is a major challenge for AM, which is why there is a great demand for this caliber of experience.

Whether you're a company owner seeking new hires to help you capitalize on the technological improvements AM provides, or an AM professional seeking greater chances, you need to acquire these abilities for the staff of the future.

D. Regulatory and legal considerations

Whether AM is used for business or personal usage, there are a lot of complex legal concerns and difficulties that come with using it. These will change based on the relevant jurisdiction..

PRODUCT SAFETY AND LIABILITY

In the context of 3D printing, legal laws governing the safety and acceptable usage of particular product categories should not be overlooked. Two relevant EU legislative instruments are the European Directive on Toy Safety (2009/48/EC) and the European General Product Safety Directive (2001/95/EC). Product safety is also an issue since the raw materials (also known as "ink") used in 3D printing could not necessarily be subject to prior quality inspections (Team, 2018).

Under the theory of product responsibility, the maker of a product may be liable for any harm caused by a defective product.

Under the notion of product responsibility, the maker of a product may be liable for damages caused by a defect in the product. When a product does not meet the safety standards that consumers are entitled to, it is deemed faulty. This is determined by considering all pertinent factors, including the product's appearance, its appropriate usage, and the date it was placed into circulation. Producers are held liable without fault under Directive 85/374/EEC. In the event that their products are advertised and sold to consumers in general, makers of 3D printers and 3D printed goods are both subject to product responsibility.

Because the rule exempts items not put into circulation by the manufacturer, a supplier who makes 3D templates and sells them to clients directly so they may print them out at home for 3D printing might not be held accountable for their products.

TAXES AND IMPORT LIMITATIONS

Import limitations may be applied to specific products by a specific nation. Money, medicine, and weapons are common examples. Selling goods 3D templates to people who live in nations where the product is subject to an import restriction may unintentionally violate the import restriction for both the buyer who prints the object and the seller of the template. Furthermore,By facilitating domestic manufacture, which may skirt restrictions on the importation of goods and any associated import duties, 3D printing speeds up traditional supply chains.In light of this quickly developing technology, several jurisdictions are currently examining their current customs laws to see if any changes are required.

COUNTERFEIT

When someone uses a 3D printer to make counterfeit coins or bank notes, 3D printer manufacturers and 3D template suppliers face the danger of being linked to counterfeiting. One technique to lessen the possibility of unauthorized use of the printer or template is to install anti-counterfeit software, which is comparable to what is used in paper photocopiers.

PRODUCT LAVELLING

Certain product categories have labeling requirements that are governed by EU rules, such as Regulation 1169/2011 regarding food items and a separate legal framework for non-food products including textiles, footwear, and cosmetics. Labeling is primarily used to inform and ensure that the customer utilizes the product safely.

The above non-exhaustive overview leads one to the conclusion that, similar to other areas of technical advancement like the Internet of Things, the question of who is in charge of adhering to the relevant regulations seems to go unanswered in the current framework.

4. Case Studies and Examples

A. Real-world examples of additive manufacturing in the supply chain

Michael Idelchik, vice president for advanced technologies at GE Global Research, projects that the company will be able to print a full engine in 40 years. It will take time to verify this, but GE Aviation is making big bets and just acquired two AM pioneers in the aviation sector, Morris Technology and Rapid Quality Manufacturing. Furthermore, GE Aviation and the French company Snecma have partnered to include AM-manufactured combustion technologies into their latest jet engines.

Boeing has been using additive manufacturing (AM) to produce aircraft parts for a long time. Air ducts for F/A-18 Hornet fighter aircraft manufactured ten years ago are among those parts.

Originally, the ducts were complex pieces made of aluminum. With FAA-approved plastic powder, they can now create air ducts as a single, monolithic component in the SLS process. The primary benefit is design freedom, as there is no need for welding or assembly, less weight, and subsequently lower costs. In order to create high-quality parts for its aircraft, Boeing uses improvements in SLS process stability and monitoring to manufacture its own high-quality material (Lions, 2012). A new concept for SLS continuous linear manufacturing for large-scale component manufacture was recently filed for patent by Boeing (US Pat Appl. 20120067501). CalRAM is another firm that produces AM components for airplanes. It was founded in 2005 as a spin-off of Boeing. It produces certified metal and plastic parts.

Aerospace combustion systems and components are designed, developed, and manufactured by Italy's AVIO Group for use in both army and commercial aircraft. In order to surpass traditional investment casting methods and produce components with extraordinary qualities, more complexity, and reduced weight, AVIO employs titanium aluminide in its EBM machinery and stainless steel as well as nickel, cobalt, and aluminum alloys in its DMLS process. Furthermore, powder alloys specifically designed for these processes are sold by AVIO.

B. Successful implementation strategies and outcomes

The most iconic examples of 3D printing in the aviation sector are the fuel nozzles and T25 sensor housing on GE LEAP jet engines. Twenty components are assembled into a single 3D printed nozzle, which weights 25% less than a nozzle made traditionally. The Federal Aviation Administration (FAA) has validated the T25 sensor as the first 3D printed component that may be used on commercial aircraft. This sensor, which gauges the engine control system's temperature and pressure, is situated near the high-pressure compressor's inlet.

GE claims that this work preserved months' worth of design and production processes without sacrificing usefulness.Utilizing 3D printing technology, other businesses have achieved time savings of 60 to 90 percent; hence, 3D printing production may be utilized to reduce the replacement part supply cycle, enhancing availability. As a pioneer in AM innovation, GE has impacted many different sectors.

Boeing's strategic approach to additive manufacturing demonstrates how a leading aerospace manufacturer can leverage emerging technologies to enhance production processes, drive innovation, and improve product performance. The company's ongoing commitment to AM indicates the growing importance of this technology in the aerospace industry (Lions, 2012).

C. Lessons gained and best practices and problems addressed during the implementation phase.

Even at this point, the use of AM has several drawbacks as compared to traditional manufacturing. These drawbacks are mostly related to quality issues and the lack of stringent quality control standards for the created parts. Despite several studies demonstrating AM's ability to create standards-compliant components, much more study is necessary to establish AM's safety record before a dependable standard is achieved.

The cost of AM materials and equipment is too expensive. The cost of additive manufacturing (AM) equipment is currently prohibitive; the higher the requirements for the quality of printed parts and the rarer the materials needed, the higher the requirements for the scientific and technological level of AM machines. As an example, an AM machine capable of producing parts for commercial aircraft engines costs roughly one million yuan. The cost of the necessary metal materials is between 500 and 800 yuan per kilogram.

Insufficient criteria for quality The aviation industry has not widely adopted AM technology because, quite obviously, the certification of 3D printed parts is the most challenging aspect of the process. Limited material processing data information and a lack of industry standards in the areas of material, process, quality assessment, and design make for an extended certification period.

Limitations on property rights. Over the past few decades, intellectual property has drawn more attention from various sectors, including music, cinema, and television. This part of the issue will also be addressed by AM technology; as technology advances, individuals may utilize machines to reproduce anything they want, indefinitely. The challenge we have is how to create AM rules and regulations to safeguard intellectual property rights in order to stop the phenomena of flooding and infringement.

5. Future Trends and Implications

A. Emerging trends, innovations and advancements in additive manufacturing technology

Over the past three years, manufacturing companies have faced increasing challenges on a global scale. Honestly speaking, it appears that the instability and unpredictability that have impacted world economies might continue in the upcoming year.

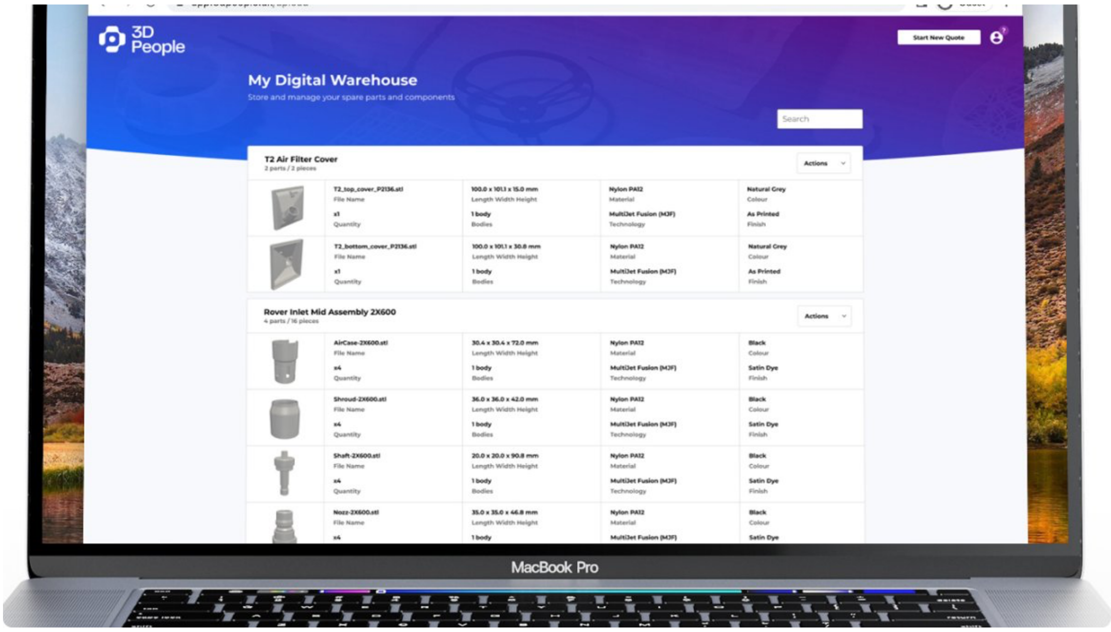
Despite growing fuel and production costs, additive manufacturing has proven to be a useful tool for manufacturers. It helps lessen losses brought on by disruptions in the supply chain and lower operating costs. By using 3D printing, businesses can manufacture necessary parts and components quickly and effectively, minimizing their reliance on antiquated supply chains that are vulnerable to disruption. enabling the on-demand production of customized parts, lowering waste and inventory expenses.

The 3D printing industry has continuously shown signs of steady growth, and the market's ongoing expansion is encouraging. In the next three years, the industrial 3D printing market—along with associated industries like 3D printing hardware and materials—is anticipated to grow to a value of over $35 billion, according to a Market and Market report. This expansion demonstrates how 3D printing technology is becoming more and more valued across a range of industries.

1. Virtual inventories

Virtual inventories, also referred to as digital warehouses, are revolutionizing the way companies handle and store spare parts and components. This technology, in conjunction with 3D printing as the manufacturing system, enables businesses to manage their inventory and produce goods as needed, doing away with the requirement for physical warehouse space.

Reducing lead times and shortening supply chains is a major benefit of digital warehouses and 3D printing. With on-demand components production and digital real-time inventory management, businesses can place orders more rapidly and more accurately decide when they need to resupply. This can shorten lead times and expedite the delivery process. In order to further cut lead times, part obsolescence, and supply chain expenses, businesses can also find more economical and efficient suppliers with the aid of digital warehouses and 3D printing.



T2 Air Filter Cover
2 parts / 2 pieces

T2_top_cover_P2136.stl File Name x1 Quantity	100.0 x 101.1 x 15.0 mm Length Width Height 1 body Bodies	Nylon PA12 Material MultiJet Fusion (MJF) Technology	Natural Grey Colour As Printed Finish
T2_bottom_cover_P2136.stl File Name x1 Quantity	100.0 x 101.1 x 30.8 mm Length Width Height 1 body Bodies	Nylon PA12 Material MultiJet Fusion (MJF) Technology	Natural Grey Colour As Printed Finish

Rover Inlet Mid Assembly 2X600
4 parts / 16 pieces

AirCase-2X600.stl File Name x4 Quantity	30.4 x 30.4 x 72.0 mm Length Width Height 1 body Bodies	Nylon PA12 Material MultiJet Fusion (MJF) Technology	Black Colour Satin Dye Finish
Shroud-2X600.stl File Name x4 Quantity	36.0 x 36.0 x 42.0 mm Length Width Height 1 body Bodies	Nylon PA12 Material MultiJet Fusion (MJF) Technology	Black Colour Satin Dye Finish
Shaft-2X600.stl File Name x4 Quantity	20.0 x 20.0 x 90.8 mm Length Width Height 1 body Bodies	Nylon PA12 Material MultiJet Fusion (MJF) Technology	Black Colour Satin Dye Finish
Nozz-2X600.stl File Name x4	35.0 x 35.0 x 46.8 mm Length Width Height 1 body	Nylon PA12 Material MultiJet Fusion (MJF)	Black Colour Satin Dye

Figure 5‘My Digital ‘Warehouse feature’ coming soon to 3D People from 3dpeople.uk database

The more companies adopt this digital inventory management and additive manufacturing strategy, the more advantageous and efficient it will be for them to store and manage their spare parts and components. (Manley, 2023).

2. Streamlined Mass Customization

There has been a discernible shift in demand in recent years toward products that are customized and made to order. Customers are moving away from mass-produced goods and toward more individualized experiences. They want products that suit their preferences and meet their specific needs. The increasing availability of options and information has enabled consumers to make more individualized and well-informed decisions, which is one of the main forces behind this trend.

For companies trying to meet this demand for customized products, additive manufacturing provides an option. Personalized products can now be produced by manufacturers in smaller quantities thanks to these technologies, instead of following fashions or oversaturating the market with identically designed goods.

All things considered, the demand for mass customization coupled with 3D printing offers a big chance for companies to stand out from the competition and satisfy evolving customer demands. Businesses may remain in the lead and satisfy the expanding market for customized and distinctive product by utilizing these technologies.

3. Recycled Materials

The current focus on sustainability has led businesses and sectors to embrace green initiatives meant to lessen their environmental effect. This push includes the use of energy-efficient technology, waste-reduction techniques, and a steer clear of non-recyclable materials. By using recycled materials, 3D printing can also promote sustainability.

Many of the filaments and polymers used in 3D printing are biodegradable and long-lasting, which makes it feasible to reduce plastic waste. In addition to recycled plastics, there are other types of recyclable materials that may be utilized, such as Nylons. By making it possible to produce unique, tailored parts and components that meet the specific needs of clients, these materials promote sustainability.

In addition to cutting waste, using recycled materials in additive manufacturing can also save costs and lessen dependency on non-renewable resources. Recycling materials will probably be used more in additive manufacturing as 3D printing gains traction as a way to boost productivity and lessen environmental impact.

4. Artificial intelligence & 3D printing

In 2022, artificial intelligence (AI) be more and more common thanks to tremendous advancements made by businesses like OpenAI and their chatGPT. It is anticipated that machine learning algorithms will impact all industries, including manufacturing.

AI and 3D printing together have the power to completely change how goods are created, used, and maintained. AI can be utilized to optimize and simplify the 3D printing object design procedure, resulting in increased productivity and a reduction in the duration and resources required. AI, for instance, can analyze a product's design and recommend modifications or enhancements depending on elements like cost, strength, and weight . AI can also be utilized to anticipate and avert possible manufacturing problems, guaranteeing the high caliber of 3D printed goods.

Artificial intelligence (AI) and 3D printing have the possible to produce individualized products that meet specific needs while also enhancing the design and manufacturing processes. For instance, AI is capable of analyzing the particular needs of a client and using 3D printing to create a product that satisfies those demands. Traditional manufacturing techniques cannot achieve this level of customization, which could significantly enhance the customer experience. Over the next 12 months, we anticipate seeing a large number of businesses integrate AI tools into their product workflow.

5. Advanced Materials

Materials science, technology, production, and research and development will work together to promote 3D printing in 2023. This partnership will create new avenues for innovation in the 3D printing sector and raise the need for hybrid materials in sectors like aerospace and technology.

Manufacturers will be able to use cutting-edge raw materials for 3D printing that are appropriate for specialized or stand-alone applications. These resources will be able to satisfy the expanding market for original and imaginative goods.

One example of an advanced material for 3D printing is a form of TPU, a polymer that can be printed at different temperatures to activate a foaming agent that changes its hardness and density. This enables producers to tailor the TPU's physical characteristics to the unique requirements of their customers. For example, a product might need a hard, rigid TPU for an app and a soft, flexible TPU for another. Manufacturers can adjust the shore hardness of TPU to meet these various requirements by varying the temperature at which the material is printed.

TPU is one of the cutting-edge 3D printing materials that manufacturers may use to create high-quality, personalized items that are suited to each customer's unique demands.

B. Opportunities for collaboration between additive manufacturing and logistics providers

For additive manufacturing to be used and flourish in the production process, material development will be essential. Materials and their diversity will be the most crucial component of transportation logistics, particularly if they are produced in massive enterprises for efficiency advantages rather than in smaller, locally distributed ones. Once at their sites, machines will be transferred, and designs can be transmitted online.Consequently, global energy consumption and greenhouse gas emissions will have an impact on material displacement.

Thus, a possible decrease in the logistics operations may be conceivable if consumer items might be manufactured locally at the desired site, cutting expenses associated with shipping and stocking. Since there won't be any intermediaries between manufacturers and buyers, the number of inventories will decrease. The task force will move to small businesses to take on new duties such as assembly line work. This new paradigm will give opportunities for new production models and controls, management models and systems, and consumer distribution even at more remote areas.

Even though additive manufacturing is growing in importance economically, it is highly unlikely that AM will be able to completely replace mass production of parts or components in the near to medium future. Its adaptability and growing material selection, however, can present a fantastic opportunity for mass customization as well as specialized manufacturing or small series. The aerospace industry, with its intricate small series production, and the healthcare sector, with its highly customized solutions tailored to individual patient needs, present the most attractive opportunities for additive manufacturing (AM) growth in the near future.Although still in the development stage, assistive technologies for the disabled are expanding quickly.

AM may have significant effects on logistics that affect downstream customer orders as well as the upstream supply chain. Since all operations will be conducted at a single location, AM will have an impact on retailers and component suppliers. This is because orders may be placed directly with the nearby factory by customers. It might result in less shipping and warehousing and more mass customization (Manners-Bell and Lyon, 2019).

C. Strategies for businesses to effectively adopt and integrate additive manufacturing into their supply chains.

Many businesses are quickly turning to digital technology in order to adapt at a time when 72% of industrial manufacturers believe that continuous shortages and supply chain disruptions present the biggest uncertainty for their industry(2023).

Many companies are realizing that additive manufacturing (AM) is becoming a more feasible choice for creating the next generation of industrial hardware products as they navigate the challenges posed by supply chain issues, economic instability, and decarbonization programs.

Using additive manufacturing (AM) to create parts with complex geometry and enhanced performance, along with its ability to speed up product development, can be a powerful way to address industry challenges. (Sun et al., 2023) The advantages of using additive manufacturing (AM) in industrial hardware to create more reliable, flexible, and efficient supply chain.

Additive manufacturing and supply chain restructuring

It is impossible to overestimate how additive manufacturing could change supply chain procedures. As new technologies replace outdated ones in the manufacturing supply chain, additive manufacturing (AM) offers numerous advantages for businesses looking to localize production and cut out weak points. This is due to the fact that AM provides a more adaptable and effective method of producing components, especially for those with intricate designs and small production quantities that frequently lead to bottlenecks in global supply chain operations.

Unfortunately, there may be a price for the supply chain resilience that AM offers. Before they can make an impact, legacy systems and components frequently need to be redesigned for AM because they usually adhere to different design standards than those used in AM. An additional significant obstacle to success is a lack of experience with design for additive manufacturing (DfAM). To optimize AM's benefits, DfAM involves designing, optimizing, or modifying a part, assembly, or product's form and function. Even with AM technologies becoming more and more common, many design engineers are still not well-versed in best DfAM practices.

Fortunately, this difficulty can be overcome with design software, which allows you to maximize additive manufacturing and lessen your reliance on experts by building, packaging, sharing, and automating DfAM processes.

Possibilities for using AM to restructure supply chains

Even though AM presents certain difficulties, there are a lot of advantages and opportunities, especially in relation to supply chain restructuring (Ekren et al., 2023). The following are a few of the most noteworthy supply chain restructuring opportunities presented by AM:

- **Lightweighting**

Lightweighting is the process of reducing the weight of a part, assembly, or system to make it as light as possible while remaining within existing design constraints.

Considerations related to the supply chain can benefit greatly from lightweighting. This is due to the fact that cost is always taken into consideration when determining whether regional additive sourcing is a viable alternative to a traditional overseas supply network. Lightweighting becomes crucial to reducing manufacturing costs because materials account for a large portion of AM's overall cost. Fortunately, AM's design freedom can greatly expand lightweighting opportunities, lowering material costs and improving component performance at the same time. Another important benefit of lightweighting that helps offset any additional expenses the process may incur is improved performance.

- **Functional integration**

Functional integration, which combines multiple functional elements into a single part, can help you avoid the need for an additional step in the 3D-printing supply chain. It also simplifies assembly, reduces potential points of failure, and lowers the cost of manual labor. There are several ways that functional integration can be implemented, including embedded systems like surface textures, compliance mechanisms, and cooling channels.

- **Architected materials**

Architected materials have a wide range of applications that can make the supply chain safer and more effective. Specifically designed to fulfill particular mechanical, thermal, electromagnetic, or biological performance requirements, architectural materials are highly engineered structures. Their uses are diverse and include everything from movable foam-like structures to eco-friendly substitutes for dangerous substances that lower supply chain risk.

Businesses should plan and do a thorough assessment to ascertain the goals and extent of additive manufacturing. Companies may identify which goods or components are appropriate for additive manufacturing and establish specific objectives, including increasing production efficiency, cutting costs, and decreasing lead times, by taking into consideration the technological benefits and features of additive manufacturing. In addition, it's critical to evaluate how additive manufacturing will affect the logistics supply chain and figure out how to work with the networks and procedures that are already in place.

Give staff training and technical assistance a high priority. Although additive manufacturing is a new technology, some businesses may struggle with a lack of technical staff and expertise. In order to guarantee that the company has the technical strength to support the use of additive manufacturing, businesses should concentrate on developing and introducing internal talent. To get the required technical help and direction, you can also collaborate with seasoned technical teams or research organizations.

Build connections with vendors of additive manufacturing that are appropriate. Companies may search for providers with professional technology and a solid reputation to deal with in order to guarantee that they obtain high-quality additive manufacturing services from vendors. Material support and highly precise equipment are necessary for additive manufacturing. In order to accomplish smooth production and distribution, it is also feasible to work together to investigate and investigate how to best integrate additive manufacturing into the logistics supply chain..

Optimize resource allocation and logistics supply chain procedures. Given the differences between additive manufacturing and traditional manufacturing, businesses can maximize the benefits of additive manufacturing by streamlining the supply chain, streamlining processes, cutting inventory, increasing transportation efficiency, etc. Simultaneously, it is imperative to logically distribute resources throughout the supply chain in accordance with the requirements of additive manufacturing. This includes the acquisition and administration of raw materials as well as the planning and oversight of storage facilities.

Lastly, businesses should continually optimize and enhance their operations while keeping a careful eye on the market and technological developments. Additive manufacturing technology is always developing, so businesses must stay up to date with the newest innovations and market demands, enhance the application of additive manufacturing techniques in the supply chain of logistics through ongoing innovation and improvement, and make sure they stay ahead of the competition.

6. Conclusion

In concluding this research, it's evident that the evolution of additive manufacturing (AM), particularly in the realm of 3D printing, is set to significantly reshape industry norms and practices in 2023 and beyond. This study has provided a comprehensive analysis of how these technologies are revolutionizing different facets of the supply chain, offering detailed insights into their implications for businesses.

A. Recap of the impact of additive manufacturing on the supply chain

Often referred to as 3D printing, additive manufacturing (AM), is transforming the supply chain in several significant ways. Firstly, it is reshaping market demand and logistics, particularly in the storage and distribution of 3D printing materials, as lower costs and growing public acceptance boost consumption potential. AM streamlines logistics operations, making them more efficient and cost-effective by reducing logistical steps, enhancing inventory management, and improving customer experiences. Customization and on-demand production are hallmarks of AM, allowing production closer to consumption points and reducing the need for large-scale, standardized product inventories. This shift to flexible, low-volume production is more responsive to real-time consumer needs. Additionally, AM offers personalization opportunities that enhance customer satisfaction by allowing unique, tailored products. It impacts traditional supply chain models by enabling decentralized production, thereby reducing storage and transportation costs while increasing responsiveness. The integration of AM in smart supply chains improves flexibility in design, product variety, and process adaptability, meeting diverse market demands quickly and efficiently. Innovations like 4D printing and nanoscale printing in AM are pushing product design and innovation, leading to more agile production schedules and reduced manufacturing times. Finally, AM contributes to environmental sustainability by reducing waste and allowing for the use of recycled materials, making it an increasingly crucial approach in industries focused on reducing environmental impact. Overall, AM is redefining the efficiency, responsiveness, and sustainability of supply chains in the modern manufacturing landscape.

B. Summary of key challenges considerations and benefits.

There are several intricate difficulties in integrating additive manufacturing (AM) into the supply chain.. A primary issue is the integration and collaboration within the supply chain, which requires a harmonious alignment among various stakeholders such as suppliers, manufacturers, retailers, and logistics companies. This process demands a shared understanding and resource allocation to seamlessly incorporate AM technologies. Additionally, AM faces technological limitations and infrastructure demands. The high cost of advanced equipment, coupled with challenges in software development and technological capabilities, especially hinders smaller enterprises. There's also the impact on the workforce and skill requirements. As AM technologies advance, there is an increasing need for specialized skills, necessitating comprehensive training and development programs for employees. Moreover, the regulatory and legal landscape around AM remains uncertain, with issues like intellectual property rights, safety standards, and a lack of comprehensive legislation posing significant challenges. These challenges highlight the need for strategic planning, investment in human capital, and an adaptive approach to regulatory compliance to successfully harness the possible of AM in the supply chain.

Conversely, the incorporation of additive manufacturing (AM) into the supply chain yields significant and revolutionary advantages. AM significantly enhances logistics operations, making them more streamlined and efficient, which includes reducing logistical steps, improving inventory management, and enhancing customer experiences. The ability to customize products and produce on-demand greatly minimizes inventory and warehousing requirements, allowing production to be more closely aligned with consumption. This leads to a shift from high-volume, standardized production to flexible, low-volume production that is responsive to real-time consumer needs. Personalization opportunities provided by AM lead to increased customer satisfaction as businesses can offer unique, tailor-made products that stand out in the market. Additionally, AM gives the supply chain more adaptability and reactivity, allowing businesses to swiftly adjust to changes in the market and broaden their product offers.. Environmental sustainability is another significant benefit, as AM reduces waste and supports the use of recycled materials, aligning with global efforts to minimize environmental impact. Furthermore, improved resource and raw material utilization through AM leads to reduced operating costs and a substantial reduction in the time required for product design and manufacturing. This efficiency, coupled with the capability to produce complex and customized products quickly, provides businesses with a notable competitive advantage. These benefits underscore the transformative potential of AM in revolutionizing supply chain operations, enhancing environmental sustainability, and driving business growth.

C. Prospects and the importance of adaptation for businesses

The industry will continue to be shaped by developments in digital warehousing, additive manufacturing, and mass customization in 3D printing in 2023.

For businesses trying to enhance inventory management, these technologies provide a number of advantages, such as tiny supply chains, lower costs, shorter lead duration, and decreased part obsolescence. Furthermore, 3D printing enables producers to create personalized and customized goods more effectively and sustainably, satisfying the growing consumer demand for one-of-a-kind goods.

We may anticipate even more advantages and improvements in productivity in the way businesses plan, produce, and store their goods as the 3D printing industry develops.

In summary, for businesses, the prospects offered by additive manufacturing are transformative, but capitalizing on these opportunities requires proactive adaptation and integration of these new technologies into their existing processes and business models.

D. Closing thoughts on the future of additive manufacturing in logistics

The future of additive manufacturing in logistics is poised for a significant evolution, driven by advancements in digital warehousing, additive manufacturing, and mass customization in 3D printing. The industry's trajectory in 2023 and beyond suggests a continuation of this trend, presenting businesses with numerous operational benefits. The adoption of these technologies leads to a streamlining of supply chains, reduction in costs, shorter lead times, and a decrease in part obsolescence, all of which enhance inventory management.

Moreover, 3D printing stands out as a pivotal innovation enabling the creation of personalized and customized products. This capability meets the increasing consumer demand for unique, tailored goods and does so more efficiently and sustainably. As the 3D printing industry matures, further advantages are anticipated, particularly in the productivity realm. Businesses can expect to see improvements in the ways they plan, produce, and store goods, indicating a transformative impact on manufacturing and logistics operations as a whole.

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