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An overview of the impact of additive manufacturing on supply chain, reshoring, and sustainability

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ABSTRACT

The paper provides an overview of the impact of the integration of additive manufacturing (AM) within the supply chain, the correlation with the reshoring phenomenon, and its effect on environmental sustainability. Implementing AM technologies simplifies the traditional supply chain and significantly reduces costs related to transport and warehousing. Furthermore, it allows for a considerably reduced production of waste. However, the high price of machinery and the lack of current knowledge prevent it from spreading widely.

1. Introduction

The supply chain (SC) is an integrated process in which suppliers, manufacturers, distributors, and resellers work together to provide a final product to customers. Achieving this goal requires various activities including the purchase of raw materials, the transformation of these into finished products, and delivery to retailers.

Within the SC, it is possible to distinguish three main phases which in turn can be broken down into minor processes:

- Procurement: it is the set of activities concerning the request for raw materials necessary for production. Some of these are stock management and demand forecasting.
- Production: includes all the actual manufacturing processes, through which the raw materials are transformed into the finished product. The sub-activities of this phase are different including product development and production schedule.
- Distribution: refers to the set of operations that aim to deliver the final good to the consumer.

Most of the supply chains that operate on a large scale are defined as supply networks as they give life to a network of partners; each stage is made up of several actors. If considering, for example, a company that assembles parts to generate a finished product, it will probably order the components from different suppliers, and in turn, deliver the product to various distributors. In turn, suppliers will rely on multiple suppliers of raw materials. It can therefore be seen how the complexity of a product and its sales volume affect the structure of an SC, which for various reasons requires the collaboration of multiple players at each level (Chopra and Meindl, 2019).

The main objective of improving the performance of the SC consists, in fact, in realigning supply with demand while simultaneously trying to contain costs and improve customer satisfaction. Organizations, therefore, are called to change their SC, for example by applying the *lean* and *agile* paradigms. A *lean* approach to production and process management essentially focuses on reducing waste (Womack and Jones, 2003). This *lean* philosophy has its origins in the Japanese automotive environment of the seventies, in an industrial context focused on the creation of essentially standard products to achieve efficiency in the use of resources and the exploitation of economies of scale. The principles of *lean* production were subsequently deepened and codified into five pillars:

1. Identification of the value for the customer;
2. Identification of the flow of value and elimination of processes that do not generate value;
3. Creation of the flow of activities that generate value so that they flow without interruption;
4. Ensure that the value stream is created by the customer;
5. The pursuit of perfection through continuous improvement.

Based on the principles described above, a *lean* SC is, therefore, a set of organizations, directly connected by flows of physical products and

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information, which work collaboratively to reduce costs and waste always to satisfy customer needs. The goal is the management of production according to the Pull logic, that is, the implementation of the production process only at the request of the market.

In more volatile markets, where companies must continually introduce new products to meet customer needs, an *agile* approach is required. The paradigm is defined as "*the ability to respond quickly to sudden changes in the reference market upstream or downstream and to effectively manage any discontinuity in the external environment*" (Lee, 2004). An *agile* SC is, in fact, market sensitive, that is, it can understand and respond to actual market demand.

Turbulent markets and increasingly personalized customer demand push companies not only to implement *lean* and *agile* approaches but to completely change their SC, redesigning the SC starting from the customer instead of the factory. This fundamental change is made possible by new technologies and in particular by additive manufacturing (AM), which pushes the shift of power constantly downstream, from producers and retailers to buyers and consumers. Its introduction is changing the SC landscape, allowing small productions to become the norm and transforming economies of scale into economies of scope. If in the past supply chains were designed for the production of large volumes and cost optimization, the so-called "demand chains" are oriented toward mass customization.

Another big change in which AM plays an important role is the shift that has been taking place in recent years from offshoring to reshoring. In recent decades, offshore insourcing and outsourcing in developing countries have been two of the most popular strategies among companies aimed at creating and maintaining a sustainable competitive advantage (Fratocchi et al., 2011). In most cases, companies have deployed labor-intensive activities to specialize in capital-intensive activities. In addition, offshoring has been implemented especially for standardized production, characterized by highly codified and easily replicable processes in low-cost countries, that is, for all activities in the value chain with the lowest added value. However, if companies initially considered only the many benefits of this strategy, the involved costs and risks later emerged. These include bureaucratic obstacles, the loss of company know-how, the lack of qualified personnel for the management of production, and the inevitable localization costs deriving from the relocation of the production site. Furthermore, the great distances and the possible opportunistic behavior of the production site or the foreign supplier have made it very difficult to negotiate, monitor, and apply the supply and organization activities; thus generating an increase in transaction and coordination costs. Its adoption has led to the management of increasingly complex supply chains that have lost the reactivity and flexibility necessary to react to the rapidly changing requirements of customers and unexpected interruptions. The increase in delivery times, for example, has led to a worsening of the level of service which in some cases has caused the loss of consumers. In addition, several problems were identified regarding the quality of the products and the flexibility of the production processes. Therefore, the difficulties encountered in the implementation of offshoring have led to reconsidering a local production approach.

Reshoring or back-shoring is generally defined as the transfer of production to the country of the parent company (Ellram, 2013). However, being a relatively new concept, to date there is no single definition in the literature. An exhaustive definition of the phenomenon is given by Frattocchi et al. (Fratocchi et al., 2014) which indicates it is a voluntary corporate strategy regarding the partial or total transfer of production (internal or external) to the country of origin to serve local, regional, or global needs. It is important to underline that the reshoring strategy is an inverse and subsequent decision to a previous outsourcing process. The activities involved can be both internal and external: a company, for example, may decide to carry out within its national plants or assign certain processes that were previously entrusted to foreign suppliers to a national supplier. The drivers that push companies to implement a reshoring strategy are not always aligned. The reasons may vary according to the goal that each company sets itself. The main reasons have been identified considering two aspects: (1) the business objective and (2) the level of analysis. As regards the first, to obtain a competitive advantage, companies may decide to keep the perceived value of the customer high or to pursue cost efficiency. At the level of analysis, the reasons why the company decides to implement this strategy are related to factors internal and external to the company. Internal environmental reasons highlight the relevance of specific company factors in the reshoring decision. The external environmental reasons, on the other hand, underline the importance of the specific factors of the country of origin and the host country in the choice.

This study aims to analyze the impact of the integration of AM within the SC, the correlation with the phenomenon of reshoring, and its effect on environmental sustainability. Starting from the literature and some case studies, the various problems were analyzed to deduce how AM can eliminate the intermediate nodes of the SC, reducing transport times and bringing production closer to the final consumer. Many innovative techniques are introduced with existing business models, however, if a disruptive technology is implemented, it is necessary to reshape or even reinvent the business model. In the specific case of AM, its introduction implies the transition from a logic centered on the producer to one centered on the consumer.

2. Additive manufacturing

The American Society for Testing and Materials (ASTM) defines additive manufacturing as "*the process of joining materials to create objects from 3D model data, usually layer by layer, as opposed to fabrication methods by subtraction*" (ASTM International, 2013). The reasons for using this technology lie in the advantages over traditional processes: the additive nature allows new design freedoms; its digital nature allows for direct manufacturing from 3D models and its tool-free nature allows for more flexible manufacturing. The combination of these characteristics allows for obtaining an economic advantage for the production of customized objects compared to traditional techniques still heavily used in mass production (Ford et al., 2016). The continuous development of additive manufacturing has allowed its use in various industrial sectors, some considered inappropriate until a few years ago: aerospace, automotive, medical, fashion, food, art, jewelry, etc.

The classification of AM processes has always been a controversial issue since the appearance of the first production techniques for the realization of objects (Jiménez et al., 2019). In the literature, there are different classifications of the various techniques. The ASTM defines a standard classification, dividing the processes into seven categories (ASTM International, 2013): binder jetting (BJ); directed energy deposition (DED); material extrusion (ME); material jetting (MJ); powder bed fusion (PBF); sheet lamination (SL); vat photopolymerization (VP). Regardless of which of these technologies is used, the steps ranging from the virtual CAD (computer-aided design) description to the realization of the final physical parts can be outlined in the following phases (Calignano et al., 2019): 1. 3D CAD model: modeling of the component using a design software; 2. Conversion to STL file: the CAD model files must be converted to AMF/3MF/STL format to be readable by the AM CAM (computer-aided manufacturing) software; 3. Transfer of the AM/3MF/STL file into the CAM software for subsequent processing and conversion into a machine file: in this step, the transferred file may require some corrections of size, position, and orientation for the construction; 4. Preparation of the machine (material loading, process parameters insertion, etc); 5. Construction of the part; 6. Removal of the parts from the construction platform; 7. Post processing: parts may require some actions including media removal, and additional treatments such as surface processing, heat treatment, etc.

The strong impact of AM on production processes is due to its advantages over traditional techniques. Being a "start-to-finish" process it is possible to create integrated parts without having to resort to multiple processes and the use of multiple machines. Using additive techniques, an assembly of parts made from the same material can be fabricated as a single piece, which reduces or eliminates the cost, time, and quality problems arising from assembly operations (Tofail et al., 2018). Furthermore, compared to the classic approach, it offers greater design freedom. From an economic point of view, the geometric complexity does not involve any increase in costs. Since the product is made layer by layer, the costs and time required to produce a complex part are essentially the same as for a simple part. Compared to conventional products such as molding, it is possible to customize and modify objects almost instantly; this allows the production to be synchronized with customer requests. A further advantage is the environmental sustainability of the process: if the traditional approach is based on subtractive processes where the object is made by removing material from an initial piece, AM processes only use the material strictly necessary to create the piece. In addition, any material not used during production (e.g. powders) is recycled and reused. As for the product, it is possible to create lighter structures by inserting material only where necessary. Through AM, it is possible to have important improvements in the SC. One example is the possibility for small producers to locate production close to customers.

2.1. Economic aspects

Compared to traditional technologies, additive manufacturing does not benefit from the economy of scale; the main reasons are speed and limited build capacity. Therefore, the mass production of standardized parts is likely to be the domain of conventional manufacturing technologies (Busachi et al., 2017; Weller et al., 2015). Some studies (Hopkinson and Dickens, 2003; Ruffo and Hague, 2007) have shown that as the units produced increase, there is a reduction in initial costs and then stabilization of the latter. Fig. 1 shows a comparison between the cost trend of AM and traditional techniques as production volumes increase.

However, this could be an advantage for companies as mass production is shifting to developing countries while the EU and US markets are more focused on small, high-value-added productions characterized by innovation, personalization, and sustainability (Busachi et al., 2017). AM allows for the reduction of the production time of prototypes and speeds up the subsequent production phases since no investment is necessary for the design and manufacture of the equipment and devices necessary for the construction of the product. This allows for reducing the total time to market. Furthermore, the technology allows the development of complex designs without having variations on the total production cost. The inputs of the machines do not depend on the geometric complexity of the piece to be made. In traditional production methods, on the other hand, high levels of product customization could lead to high production costs. This is due to the significant investments in production line modifications. Fig. 2 shows the trend of the costs of AM and traditional processes as the geometric complexity increases (Busachi et al., 2017).

Product customization potentially produces an increase in the perceived value of consumers and therefore a greater willingness to pay. This is why companies can charge a premium and generate more profits. AM allows customers to co-design products that are perfectly suited to their requests. Numerous websites already allow consumers to create individual products by altering design parameters; the customized 3D models are then produced directly with AM technology. In the future, therefore, the variety of products can become potentially infinite very high (Weller et al., 2015).

2.2. Limits of the AM

Despite the many benefits, some limitations prevent the technology from being fully implemented. The main disadvantages of the process are restrictions on dimensions, production times, and the purchase costs of machines and materials. Compared to traditional techniques, AM processes are relatively slow. While there is no waiting time between production runs, the total build time is longer than the production times of conventional processes. Consequently, unless there is the possibility of increasing the print speed if large quantities are required, conventional production remains the most preferred method of construction (Cotteleer, 2014). The limits relating to the product are the presence of supports and imperfections. In most AM techniques it is necessary to insert support structures to make the object, these generate, in the contact areas between the support and the piece, greater surface roughness and the need for a post-treatment process to separate the two elements (Cotteleer, 2014).

Furthermore, despite the surface finish and therefore the presence of imperfections, surface roughness varies according to the techniques and machines adopted (Calignano et al., 2022); the final results are always lower than those obtainable with subtractive processes; therefore, if the required finish is particularly high, further processing is required.

2.3. AM and supply chain

Among the various technologies of Industry 4.0, the implementation of AM allows for simplifying the SC by increasing efficiency and responsiveness in the fulfillment of demand. In recent years, various supply chain concepts have been developed. AM allows them to be applied practically, guaranteeing the creation of value within the SC.

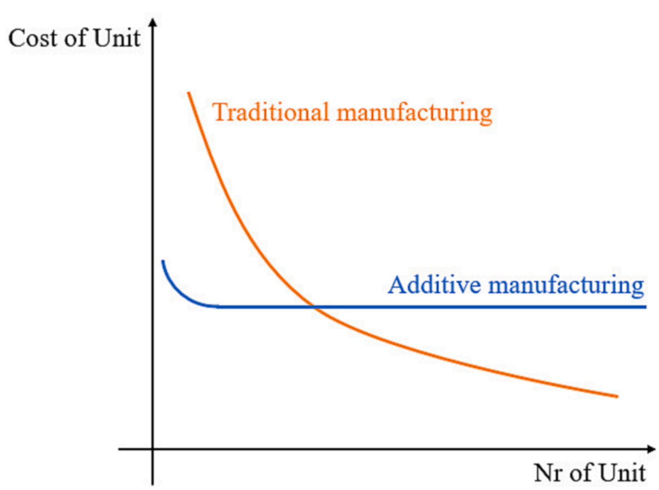

Fig. 1. The trend of the cost function with the units produced (Busachi et al., 2017; Hopkinson and Dickens, 2003).

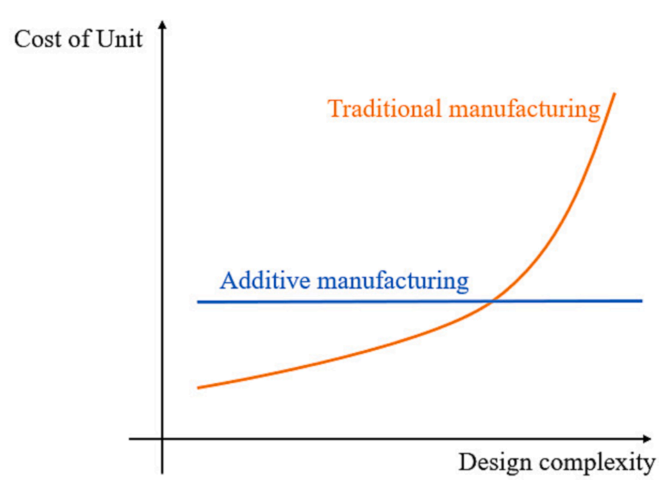

Fig. 2. The trend of the cost function with geometric complexity (Busachi et al., 2017; Hopkinson and Dickens, 2003).

The fundamental principle of the *lean* approach is the reduction of costs and waste to invest only in activities that generate value for customers. Since AM allows the production of an object through a single process, its application allows the elimination of the stock of semi-finished products (WIP, Work in Progress). In addition, the integration with other technologies of Industry 4.0 will allow companies a just-in-time production compared to just-in-time warehouse management. Redesigning products with fewer components also provides additional savings on the cost of procuring parts and components not manufactured in-house. In addition, since it does not require tool changes for the machining of different parts and products, it allows for the reduction of the set-up times of the machines (Tuck et al., 2007).

If the company operates in turbulent markets, characterized by variable demand, and produces products with an ever shorter life cycle, the *agile* approach becomes effective in achieving a competitive advantage. In these conditions, it is necessary to increase the flexibility of the system. The manufacturing flexibility of AM allows for the rapid reconfiguration of products and processes in terms of both quantity and design to meet changing consumer demand. The AM allows moving the decoupling point of the order (the point where the customer is linked to the product) closer to the customer within the SC, significantly increasing the flexibility of the SC. In practice, the company could produce according to a make-to-order logic in which the customer determines the production not only in terms of volumes but also of product characteristics (Tuck et al., 2007).

In many sectors, the ability to customize products is essential to survive in the market. AM provides all the benefits of mass customization, namely: relatively low part production, reduced inventory risk (products are made only after orders have been received), and better working capital management (payment occurs earlier in production), limiting, however, the resulting disadvantages. Mass customization requires a highly integrated SC, as the components used to manufacture the products come from different suppliers; in contrast, AM uses consumables that can be purchased from multiple suppliers (Berman, 2012).

2.4. SC reconfiguration

The use of additive techniques not only influences the customer's involvement in the design phase but offers the opportunity to have decentralized structures located close to the consumers. Therefore, based on their needs, the characteristics of the product offered and the market in which they supply, companies have the possibility of integrating additive technology in a centralized or decentralized way within their SC (Holmström et al., 2010). The use of AM in a centralized system implies the realization of the products in a central office and the subsequent shipment to the various distribution centers. Although this approach does not allow the reduction of transport times, it allows the aggregation of demand, coming from the various centers, so that the investment in the capacity of AM machines is used efficiently. The centralized approach is appropriate when the quantity demanded on the market is limited and lead time is not a critical factor (Fig. 3a).

On the contrary, in distributed AM, production takes place in each distribution center, allowing the elimination of storage costs, the reduction of transport costs, and a faster response time (Fig. 3b). Barz et al. (2016) conducted a computational study on the impact of additive manufacturing on transport costs. Their research showed that the introduction of technology and the new repositioning of production sites leads to a reduction in transport costs from a minimum of 43% to a maximum of 58% (Barz et al., 2016). In addition, making a few products in multiple factories allows for an SC that is less vulnerable to disasters and disruptions; the impact is no longer national or regional but localized in a single place of employment. In addition, decentralized production allows companies to explore the different markets in which the distribution/production centers are located, thus adapting production to these. However, its implementation requires high investments in 3D machines and specialized personnel justified only in case of high demand.

Generally, the SC can be divided into three primary levels: upstream, midstream, and downstream. Upstream there are raw material and spare parts suppliers and manufacturers, midstream includes transport and warehousing processes, while downstream includes resellers and distribution of finished components to end customers. Between these levels it is possible to identify five types of flows that interconnect suppliers, producers, wholesalers, retailers, and consumers: product flows, process flows, information flows, financial flows, and energy and natural resources flow. Fig. 4 shows a traditional SC, a centralized AM model, and a decentralized network reconfiguration model considering these flows. The SC in the conventional manufacturing setup includes several stakeholders from material suppliers and component suppliers to the final customers.

In the centralized model, the AM machines are installed in centralized locations at the upstream levels. In particular, these are used by both original equipment manufacturers and spare parts suppliers. A hybrid approach is used: AM is not a substitute for traditional

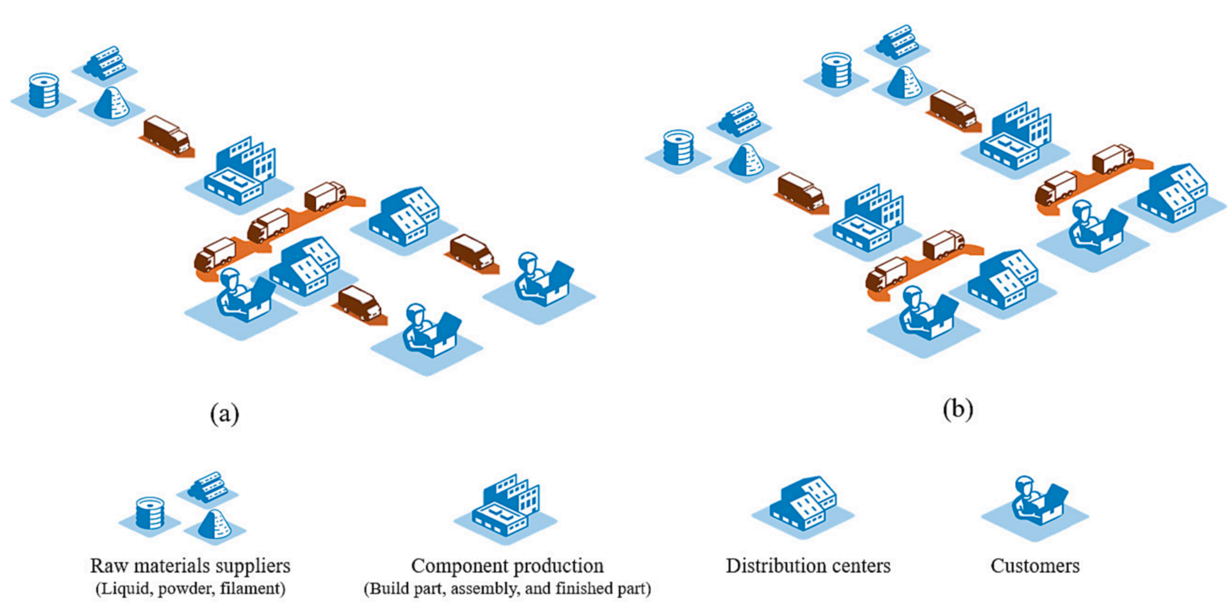

Fig. 3. (a) Centralized and (b) distributed AM.

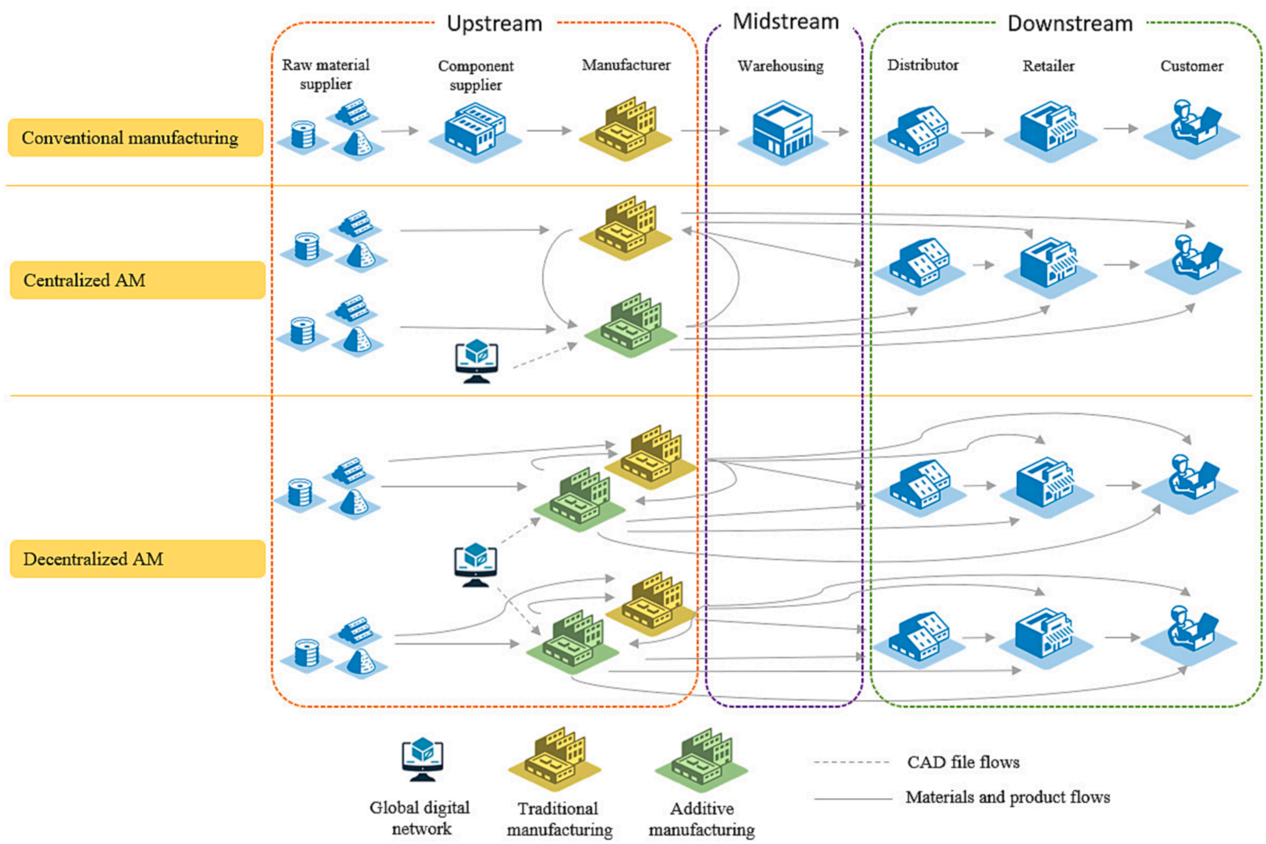

Fig. 4. SC reconfiguration.

manufacturing but a complement (Tziantopoulos et al., 2019). Furthermore, there is a transfer of digital flows through the 3D CAD file that can reach the company through a global digital network. Centralized production allows integration with the e-commerce channel. Through the AM it is possible to implement production which allows customers to create their products and to transfer files in one place for manufacturing; this facilitates the relationship between the final customer and the organization without the need for intermediaries such as channel resellers (Eyers and Potter, 2015).

In the decentralized model, assuming that future technological improvements and the widespread use of AM will reduce the cost of these technologies, especially those for manufacturing metal parts, the machines are installed in distributed locations. This leads to shorter and less complex supply networks, fewer transport needs, and shorter delivery times. Decentralized production will lead in the extreme case to user production (Fig. 5). This hypothetical model has the potential to significantly influence the SC. Consumers will no longer buy physical products from companies, only CAD files that will be self-produced using technologies located in their homes (Fig. 5b) (Eyers and Potter, 2015). Home printing, however, challenges current intellectual property (IP) rights. This has led to the beginning of a scientific debate as to how AM

Fig. 5. (a) 3D shop SC; (b) home printing SC.

can affect nearly any form of IP law, including copyright, design law and patent law (Ballardini et al., 2022; Wang and Rimmer, 2021; Widmer and Rajan, 2016). Using IP law can help creators protect their work and determine how others can use it. This in AM means that if an object is copied and manufactured without the permission of its creator, it may suffer consequences under copyright law. However, there are still gaps in the law in this area especially in the field of personal use.

In addition, the customer-to-customer (C2C) business model will spread through which customers will purchase products from other customers, thus spreading production without producers.

Another future development is the possibility for companies to implement an outsourcing strategy. Since design and production are easily separable in AM, companies can entrust production and delivery phases to companies, focusing only on product conception. Outsourcing allows access to technology without the high capital investment costs; thus lowering the barriers to entry for entrepreneurs. In addition, the availability of these services offers sustainability benefits through the increased use of equipment. Alternatively, companies can integrate the AM by renting or sharing machinery with other companies (collaborative production). However, to make these changes to the structure of the supply chains, a company commitment is required in redesigning both products and processes to simplify their SC and change their role within it.

2.5. Organizational changes

The introduction of AM techniques requires designers and engineers to modify the entire production flow (Mellor et al., 2014). While the new process offers important design advantages, on the other hand, it involves a redefinition of roles and skills within the company. In most cases, the staff does not have the necessary knowledge to use the technology; consequently, it is advisable to hire specialized employees or train the staff already present (Mellor et al., 2014; Oettmeier and Hofmann, 2016). Another important factor for its introduction is the relationship with suppliers. As previously mentioned, the production of the objects through a single step allows easier management of the relationships upstream of the SC; it is not necessary to purchase multiple components from various specialized manufacturers, but replenishment can be done through a few suppliers. However, on the one hand, there is an increase in procurement standardization, on the other hand, close collaboration with suppliers of machines and materials is a critical factor for the success of the implementation. In fact, in the initial stages, companies must work closely with 3D machine manufacturers to acquire sufficient skills to understand the characteristics of printers and materials. In addition, the transition from traditional production to AM increases the importance of having a long-term production plan mainly due to the high investment required to purchase the technology.

Another aspect to consider is the diffusion of AM service providers. Initially these companies mainly offered rapid prototyping services to help companies in product development. As AM technologies have evolved, and so has knowledge, there are emerging service providers, AM factories, who focus on producing custom final parts for both businesses and consumers. More and more companies are entering the industry offering not only rapid prototyping services but also small batch production, creating a global network of companies which are then starting to create distributed manufacturing. At the same time, the largest AM service companies are now evolving into true AM factories, introducing higher levels of automation and streamlined end-to-end digital workflows for digital additive mass production.

2.6. Case study: AM in the SC of spare parts

Numerous researchers (Holmström et al., 2010; Khajavi et al., 2014; Oettmeier and Hofmann, 2016) have focused their attention on the SC of spare parts, focusing in particular on the aeronautics sector. This industry is an example of how crucial the speed of repairs is for the creation of value for consumers. Consequently, for there to be a quick repair and maintenance service, good availability of spare parts and therefore an efficient SC of these is required. However, it is nearly impossible for an airline to have all the necessary parts in stock; just think, for example, of the large commercial aircraft built by Boeing or Airbus made up of 4 million pieces (Walter et al., 2004). The use of traditional production techniques involves numerous inefficiencies for companies in the sector. To highlight one of the main problems it is necessary to classify spare parts (and therefore parts of an aircraft) into two categories: standard and non. For the former, it is possible to forecast demand and plan production, as these parts need to be replaced at regular intervals according to a maintenance schedule. Most of the pieces, however, are rarely needed and are called slow-moving parts, that is, parts that are generally not very busy. The need to have this category in the warehouse represents a high cost for companies both in terms of obsolescence and invested capital. In many cases, warehouse and logistics costs are disproportionate to the cost of production. The unpredictability of demand and the high resulting costs have led scholars and companies to consider AM as a solution to the problem of inefficiency. The implementation of centralized AM, in place of the warehouse, reduces the need to maintain safety stocks. Specifically, it is possible to divide the items into three groups: A, B, and C. The first is the fast-moving ones (previously referred to as standard), these represent about 80% of sales and only a small part of the management costs of the warehouse. The remainder, B and C, increase inventory management costs without, however, contributing to the profitability of the company: parts B represent 50% of the pieces and account for 15% of sales while parts C constitutes 30% of items in stock and only contribute to 5% of sales. The introduction of AM to produce slow-moving items reduces high warehouse and logistics costs subsidized with profits from the sale of fast-moving parts. In essence, manufacturers could continue to produce standard parts using traditional techniques, transporting them to a centralized warehouse, and at the same time produce, through centralized AM, the less requested parts. This solution allows both to reduce stock levels and to fully exploit the production capacity of AM machines.

Centralized AM, however, does not solve the problems of transport times and costs; if it is necessary to provide the service in a remote location in a short time, the only solution available at the moment is the presence of a decentralized warehouse at the site. An alternative to this is the use of distributed AM (Walter et al., 2004). The location of production plants not only influences the configuration of the SC but also has an impact on the economic aspects of the company including lead time, the level of service offered, and profitability.

2.7. AM and sustainability

The benefits of AM can be seen at different stages of the product and material life cycle (Fig. 6) as highlighted by Despeisse and Ford (Despeisse and Ford, 2015). The adoption of AM allows objects to be redesigned by improving their functionality. The CAD model allows for modification of the specific requirements of the product according to its use. Improvements to the new structures incorporated within the components include increased strength and stiffness, energy efficiency, and corrosion resistance (Ford and Despeisse, 2016).

Furthermore, with an optimized design, it is possible to achieve a reduction in the weight of a piece in a range of 35 to 65% (Villamil et al., 2018). This possibility becomes particularly useful when a component has to be assembled in a transport system since the lightness translates into a reduction in fuel and related CO_2 emissions (Ingarao and Priarone, 2020).

One of the sectors that have benefited most from additive technology is aerospace. The production of aircraft components has a negative impact on the environment, substantially caused by the excessive waste of material during traditional production processes. The high *buy-to-fly* ratio not only affects the costs of the industry but also contributes to the problems related to environmental sustainability. In recent years, product redesign through AM has made it possible to significantly reduce these problems. GE's Alabama factory nozzle printing for LEAP jet engines is a good example of how a 25% weight reduction led to a 20% decrease in fuel consumption and a 10% increase in power (Ghobadian et al., 2020).

Furthermore, the redesign can lead to the creation of simpler products that require fewer components and materials, this allows a decrease in material flows with a consequent reduction of the environmental impact along the entire SC.

In addition to the benefits of product design, the integration of AM can bring about improvements in the design of the manufacturing process. Thanks to the integration of components made using additive techniques (for example molds and tools) the production process can become more efficient both from an energy and resource use point of view. One example is Salcomp, a Finish company that is world leader in the production of electrical sockets and power supplies for mobile phones. The Salcomp operates in a high-volume sector, in which costs and efficiency are the main driving forces in maintaining a competitive

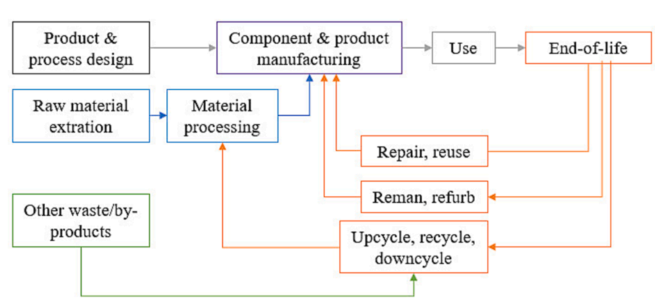

Fig. 6. Stages of the product and material life cycle (inspired by (Despeisse and Ford, 2015)).

position. In achieving the production efficiency of its Chennai plant, the company identified cooling time in the injection molding process as one of the limiting factors. For this reason, the collaboration with EOS GmbH, the German developer of the laser powder bed fusion machines for metal and polymer, was born. Thanks to the partnership Salcomp engineers were able to redesign the ventilation structure of the molds, used during the production process so that the heat was dissipated more quickly. These molds were then produced using laser powder bed fusion technology. The main benefit of the redesign was the reduction in cooling time from 14 s to 8 s, which enabled the production of 56,000 more units each month. A secondary benefit was a quality improvement, with rejection rates reduced from 2 to 1.4% (Ford and Despeisse, 2016; Salcom and EOS GmBH, 2014).

2.8. Critical raw materials

The raw materials used for additive technologies offer various opportunities for improving environmental sustainability. Just as there are various AM techniques, there is a significant variety of materials used as inputs; the nature depends on the specific process. The four main categories are liquid, filament/paste, powder, and solid sheet. Critical raw materials (CRMs) are various metals and non-metals defined as crucial for the economic progress of Europe. CRMs are essential prerequisites for developing strategies in sectors such as renewable energy, electric mobility, defense, aerospace, and digital technologies. Fig. 7 shows the CRMs for metal AM technologies. AM can reduce, replace, recycle and mitigate the use of CRM in traditional manufacturing components.

The so-called "closure of the product life cycle" can be obtained in different stages and affect AM in different ways. The highest recovery value is achieved locally in the production process during which the unused material is introduced back into the production cycle. For metal powders, it is estimated that 95–98% of the raw material used can be recycled and reused (Ford and Despeisse, 2016). Cacace et al. (Cacace et al., 2020) demonstrated that it is possible to produce powders for metal powder bed laser processes using recycled material in the atomization step. This leads to a reduction of the environmental impact of AM technologies not only on the process itself but on the entire SC.

In-situ recycling systems can be connected with AM, meaning that the materials that have now become waste to be disposed of are reused in new applications. In this context, initiatives such as *Better Future Factory* help raise awareness and educate consumers on the recycling of materials such as plastics. The *Perpetual Plastic Project* (PPP) analyzes the possibilities of reusing this material as input for 3D printing.

The collaboration between EKOCYCLE, a brand launched by will.i.am and Coca-Cola®, and 3D System has made it possible to create the EKOCYCLE CUBE 3D printer. In line with the brand's goal of sponsoring recycled products, the technology uses a new filament made, in part, from recycled plastic bottles. The company's objective is the possibility of collaborating with the most influential brands ranging from the high-tech industry to the art one, proposing a product that emphasizes recycling and encouraging to consider waste not as such but as a real and own resource.

In addition to the reuse of plastic, a strong environmental impact is provided by the possibility of regenerating the components. The Caterpillar company, a leader in this process, adopts new innovative repair techniques (including AM) for many of its engines, thus reducing waste, lowering the production of greenhouse gases, and decreasing the need for raw materials.

Several studies have been conducted focusiong on the waste recycling of AM thermoplastics (Di and Yang, 2022; Polládk et al., 2019). In order to recycle and reuse waste materials such as failed parts, support structures, and filaments in 3D printing in case of machine malfunctions, abandoned parts, and used parts due to insufficient properties or functionality, a mechanical process was developed to transform waste pellets into reusable filaments for extrusion-based AM (Cruz Sanchez et al., 2017). Kreiger et al. (Kreiger et al., 2014) performed a life cycle analysis considering recycling polyethylene filament: about 80% of energy can be save when using a properly distributed recycling operation.

2.9. AM and reshoring

Fratocchi (Fratocchi, 2017) conducted an exploratory study to

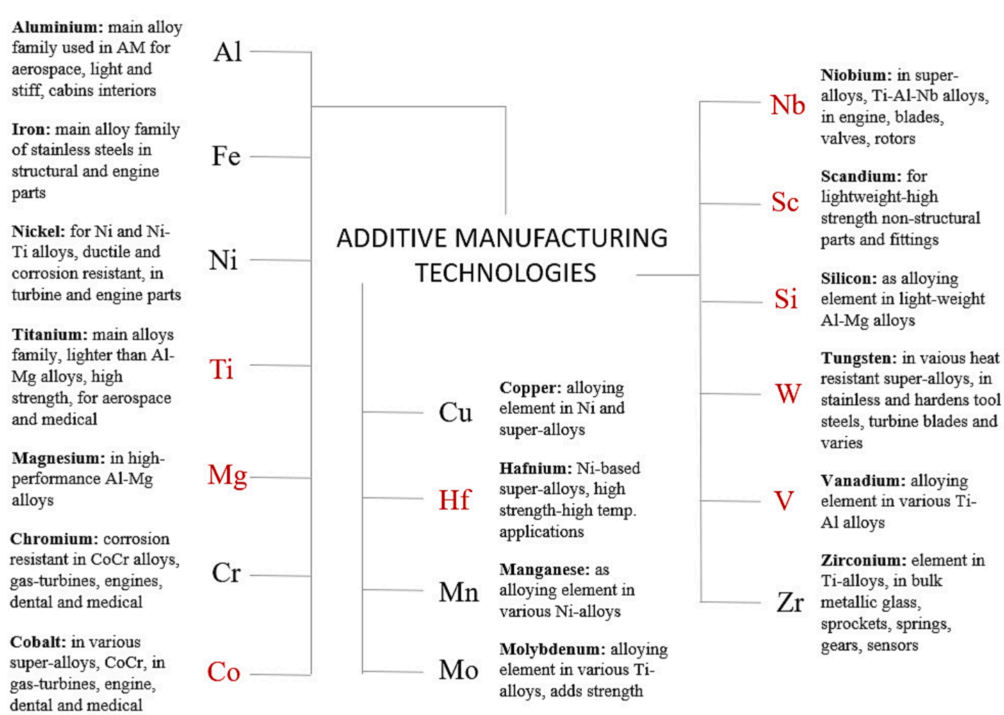

Fig. 7. CRMs material in metal AM technologies (indicated in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

demonstrate whether AM has the potential to support reallocation strategies. The research analyzed a sample of 728 reshoring decisions taken by 600 companies (some of these have implemented the strategy several times), identifying the main motivation for each. The main reasons are:

- Logistic costs: AM has a strong impact on all costs related to the SC. Its implementation allows for the elimination of the assembly phase and reduces the need for stocks in the warehouse.
- “Made in” effect: in this case the advantage of the AM is indirect; its adoption within the country of origin allows the production of products that benefit from the “made in” effect.
- Reduction of cost differentials: also in this case linked to the absence of the assembly phase.
- Total cost reduction: in the case of small batches it is possible to have a reduction in production costs as no specific tools are required. In addition, savings are achieved thanks to the reduction of material waste and the possibility of economically manufacturing complex parts.
- Improvement of the level of service and delivery times: the rapidity of the design modification allows the creation of customized products, improving the service offered to the customer. Furthermore, the ability to locate plants in places close to consumers significantly reduces delivery times.
- Government aid: in some cases, companies are forced to return to their country of origin thanks to the numerous incentives that states offer.
- R&D proximity to production: the remoteness of production from research and development activities harms innovation. In most cases, companies that decide to implement reshoring to encourage the process and product redesign implement digital technologies to do so. Specifically, the characteristics of AM offer a significant advantage in the product design phase and allow the reprogramming of the production process making it more streamlined and flexible.
- Reduction of coordination costs: the reshoring decision in itself reduces the costs of monitoring and control due to the complexity of the global SC. The adoption of centralized AM, in addition, can lead to a further decline in these thanks to the simplification of the SC.
- Minimum batch sizes: the reshoring strategy is mainly implemented as a corrective action to previous evaluation errors in the choice of relocation. The failures are mainly due to the lack of information about the foreign destination and to poor analysis of the costs and investments that this strategy entails; in some cases companies oriented to maintaining cost efficiency tend to relocate by imitation and not based on reliable assumptions in the long and medium term (Kinkel and Maloca, 2009). This phenomenon occurs especially for companies that have batch production, for which offshoring is certainly an unprofitable choice. The introduction of AM is, on the contrary, a strategically more suitable decision to achieve the goal of efficiency.
- Organizational flexibility: the introduction of AM involves a change in business processes; all phases of product creation, from design to actual production, must be redesigned according to a new perspective. However, if on the one hand, this involves an important investment in knowledge and technology, on the other it improves business flexibility. An example is the reduction of time from the prototyping to the production phase; in fact, once a prototype has been tested it is possible to make it and offer it to the market in a short time without the need to modify the production line. Still, design changes in response to customer needs are made promptly.
- Environmental sustainability: through AM it is possible to improve the eco-sustainability of products; an example is parts of cars and airplanes which, produced through additive techniques, turn out to be lighter thus contributing to the reduction of fuel consumption. In addition, unlike subtractive processes, the implementation of AM allows it to significantly reduce the production of waste.

An important aspect to consider is the relationship between the implementation of these technologies and the choice of reshoring by companies. In particular, Industry 4.0 and COVID-19 can be a driver or a consequence of the return strategy of production activities. Research conducted by Ancarani et al. (Ancarani et al., 2019) states that companies have explicitly cited advanced robotics and additive manufacturing as the reason for reshoring. This highlights how companies are attracted to technologies mainly related to the improvement of production and design activities, rather than the benefits of digital integration.

2.10. Changes in the governance model

Offshoring and reshoring involve a decision on the governance model that the company wants to follow, that is, a choice between insourcing and outsourcing. If in most cases the model adopted for delocalization was outsourcing, current research suggests that the phenomenon of reshoring leads companies to prefer vertical integration. Specifically, reshoring insourcing is significantly related to the use of Industry 4.0 technologies. The first reason is the desire to reduce transaction costs and simplify monitoring and control activities thanks to the use of new digital technologies. In addition to economic considerations, the choice sometimes depends on exogenous factors, many companies return production to countries where the supplier base has drastically decreased, thus requiring the replacement of traditional work with new technology (Ancarani et al., 2019).

2.11. Case study: AM in medicine

Coronavirus (COVID-19) severe acute respiratory syndrome has highlighted some issues related to supply chains in medical equipment and personal protective equipment (PPE). The manufacturing community’s use of AM processes has demonstrated great innovation, agility, and flexibility to fill SC gaps and shortages. In the context of the response to a global health emergency, decisions had to be made quickly, in some cases bypassing device safety regulations. The resilience of supply chains has been tested with the closure of crucial facilities and a drastic increase in demand. The transition from linear SC to intertwined digital power networks was necessary and thanks to the Internet of Things (IoT), supply networks have become dynamic and interconnected, demonstrating greater resilience to outages. Improved visibility and real-time mapping of supply and demand have been created (Ivanov and Dolgui, 2020), which is essential to meet the urgent demand for critical supplies. To meet demand, World Health Organization (WHO) has asked governments to increase production by 40% (Parry and Banks, 2020), which has led the global manufacturing industry to support the response to COVID-19 by producing designs, medical equipment, medical testing equipment, PPE, and manufacturing equipment (Sinha et al., 2020). Compared to metallic AM, polymeric AM is increasingly present in universities, schools, maker spaces, and, for many enthusiasts, in their homes. This widespread community of users using polymer additive technologies with low-cost machines (commonly referred to as 3D printing) has formed a response network to contribute to the rescue effort of PPE and medical equipment by manufacturing devices on their 3D printers (Gallup et al., 2020; Pearce, 2020; Sinha et al., 2020). A “citizen supply chain” was therefore created (Equbal et al., 2021). The AM community has actively shared projects, digital files, and knowledge across digital networks, making it easy for anyone with access to a 3D printer to contribute. The citizens’ supply chain was supported by large 3D printing companies, including Prusa® (Prague, Czech Republic) and Copper 3D® (Santiago, Chile). A visor design proposed by Prusa® was downloaded about 200,000 times in 2 months, with community users encouraged to improve the design. Likewise, Copper 3D® encouraged community collaboration to improve the design of their “Nanohack” antimicrobial face mask. With such a large contribution, the citizen supply chain is naturally decentralized and operates worldwide through a digital connection. Decentralized manufacturing generally offers some protection against external disruptions and delays seen in centralized manufacturing models using shorter and more direct supply chains, in turn allowing for faster acquisition of essential products and components. By operating locally, manufacturers can improve their responsiveness and supply–demand directly by reducing SC complexities. The positive results of localized manufacturing include shorter lead times and in some cases lower costs.

Many additive technology companies have changed their production lines to meet current needs and this has highlighted the benefits of AM such as flexibility, versatility, and reduced time-to-market. The companies have worked to rapidly release certified medical devices. Examples include Resolution Medical® (MN, USA), which has developed US FDA-approved reticular swabs using Carbon™ AM technology, Concordance Healthcare Solutions® (OH, USA) led to the production of approved swabs using Formlabs Stereolithography technology capable of producing 650 swabs on single 3D printer in 24 h.

3. Conclusion

The new technology makes it possible to eliminate intermediate nodes in the supply chain, reducing transport times and bringing production closer to the final consumer. In the extreme case, the customers could become producers, eliminating the physical flow throughout the SC. The analysis of the impact of the reshoring decision has confirmed that proximity to customers combined with design flexibility is the main advantage of adopting AM technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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