Chapter

Additive Manufacturing-Based Supply Chain Configurations

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Abstract

The topic of the chapter “Additive manufacturing-based supply chain configurations” is about the implementation of additive technologies in conventional supply chains and the possible supply chain configurations that can be generated. As a guideline in the field of supply chain management, this chapter suggests designing the AM-based supply chain configuration according to the supply chain strategy decided by the focal company of the supply chain. Two questions are not fully resolved in doctrine: the first concerns the measurement of the effects of additive manufacturing implementation in conventional companies and supply chains: the second, the relationship between the total average unit cost and the production volume of additive products. In agreement with some scholars, quantitative approach to the analysis of the impact of additive technologies in companies and supply chains is recommended, and the choice of a simulation method for ex-ante assessment of pros and cons of additive technologies over conventional ones is suggested. The goal of this chapter is twofold: to demonstrate that the superiority of additive manufacturing over conventional one cannot be discussed a priori, because it must be proven quantitatively on a case-by-case basis; to support the thesis according to which additive machines can achieve economies of scale.

Keywords: additive manufacturing, supply chain, simulation, economies of scale

1. Introduction

Additive manufacturing (AM) does not take place by removing material from a solid, as in conventional or subtractive production, but by adding material, that is, by overlapping layers of materials (such as ceramics, metals, plastics, etc.) in sequence, starting from a 3D (virtual) design that contains all necessary information to create the product, generated using CAD design system or by scanning already an existing object in 3D (reverse engineering).

For additive machines to understand and process this information, a 3D design file must be converted into an STL file (Standard Triangulation Language). By means of a slicing program, information contained in STL file is converted into G-code (machine language). Each slice of an STL file represents a layer of the product to be made by overlapping and by means of an additive machine, using different methods of material extrusion and layer solidification [1, 2]. Time required by the additive manufacturing process depends on product size; specific additive technology adopted; raw material used and degree of precision required in product realization [2].

In fact, there are many additive technologies available to companies. Among these, 3D printing, often but erroneously, considered synonymous with additive manufacturing [3].

Additive raw materials can be in form of powders, filaments, liquids, or solids. Additive manufacturing processes also use food composites, such as pasta and chocolate, and metal-ceramics, but also materials that are difficult to process by means of traditional subtractive production processes, such as carbon alloys for high temperatures, as well as, more recently, "living" biological materials, such as cells and biological tissues [4, 5].

Additive machines require little manual labor and few operational skills, but they postulate new work skills (e.g., in design), rich in knowledge, generating new organizational roles and responsibilities. Likewise, they do not require production equipment, thus removing the costs of retooling machines. Additive production is, in fact, also called "fixture-less layered manufacturing" because it occurs simply by sending a digital 3D design file to an AM machine without equipping it with tools and molds.

By conveying the manufacturing process in a virtual environment, additive technologies enable digital transformation of manufacturing.

Implementation of additive technologies in companies and supply chains can produce destructive effects on traditional production paradigms and supply chain structures, foster disintermediation and production decentralization, making supply chains lighter or more concise [4–8]. As it will be better explained later on, effects produced by additive manufacturing implementation in conventional technology supply chains depend on the value chain strategy adopted by the focal company and, therefore, on the logistic tier affected by the chosen additive technology.

In the current stage of the evolutionary process they have reached, additive technologies have not yet completely replaced conventional ones. They often integrate, support, and coexist with conventional technologies in companies and supply chains [9], being used in productions with high product customization (e.g., in the healthcare sector) and/or characterized by low or uncontrollable demand (large spikes and dips in product demand) [10–12].

2. Implementation of additive manufacturing technologies in conventional companies

2.1 Advantages of implementing additive technologies in conventional manufacturing-based companies

As regards the implementation of additive manufacturing technologies, it is necessary to distinguish between two different and distinct levels of analysis: company and supply chain.

Implementation of additive technologies in business processes is the result of a strategic decision of pure or tailored postponement [13] in a context of cost-effectiveness: additive technologies entrust product differentiation to design activities of value creation, optimizing organizational flexibility and, at the same time, making production of units or small series of items requested in a discontinuous and unpredictable way and/or with complex geometries, cheaper than in conventional production [14].

A postponement is an approach to value creation process. It takes place when one or more value creation activities are postponed at the very moment of receivement of customer order: the goal is product customization [15]. The company that postpones value creation activities waits to know what the customer really wants (form), where he wants it (place), and when he wants it (time), before starting the design and/or production and/or delivery of the product, so that this is exactly as requested and/or delivered according to the customer's place and time requests.

In this regard, some scholars describe various types of postponement strategies, each of which is according to the specific activity that is postponed. Then, they talk about form postponement strategy, if manufacturing and/or design is delayed, place and time postponement strategy, if delivery is delayed [16–18].

Order penetration point (OPP)—also referred to as customer order decoupling point (CODP)—is defined as the stage in value chain where customer order enters and product differentiation takes place. The further upstream in value chain the customer's order is placed, the greater the degree of postponement adopted by the company, therefore the greater the differentiation and degree of customization of the product. Pure or tailored product customization is achieved if product design is postponed, allowing the customer to intervene in this phase of value creation.

Postponement strategies make company—but also, as it will be said later on, supply chains—efficient in dealing with demand uncertainty [17–19]: in fact, more precise information about form, time, and place of delivery of product, and also about the amount to be made, can be obtained during postponement period, making company able to satisfy demand in form/time and/or place required, therefore agile and flexible.

Therefore, it can be said that, in contexts of environmental uncertainty, efficient companies (and efficient value chains) are those oriented toward postponement strategies, and that efficiency goes through flexibility.

So, the degree of postponement adopted by a company is a function of the level of external uncertainty to be faced and managed.

In conclusion, postponement is the "keystone" of mass customization and a tool for managing environmental uncertainty [19, 20]. Company that adopts postponement in value creation process, demonstrates that it has strategic capabilities for achieving product differentiation in one of the stages of value creation, downstream or upstream of manufacturing [21].

Implementation of AM technologies in a company allows to entrust product differentiation to value design activities and satisfies organizational flexibility needs of all sorts. These value activities enable the company to pure customization, moving CODP up to the product concept stage.

About that, Olhger [22] and Verboeket and Krikke [23] specify that, when AM replaces conventional production in a value creation process, OPP tends to move upstream, in parallel generating the shift of make-to-stock (MtS) production logic toward make-to-order (MtO) or engineer-to-order (EtO) ones. In other words, additive manufacturing makes internalization of customers in value creation process concrete, which becomes "value co-creation with customer process" as a result [14].

Generally, the full participation of the customer in the value creation process takes place by means of co-design platforms. So, additive technologies reveal the potential for pure customization if co-design platforms are active [14, 20].

Numerous scholars have addressed the issue of the pros and cons of additive manufacturing compared to conventional one. To the aim of implementing an additive manufacturing technology in a company or in a supply chain, and as an indication of a decisional method, pros and cons of a hypothetic additive plant compared to actual conventional one have to be matched with each other in a trade-off evaluation.

The topic of implementation of additive technologies in a company will be dealt with in this paragraph, reserving the following one to that of the implementation of additive technologies in conventional supply chains.

Additive manufacturing allows the company to carry out product differentiation and customization “without extra costs” [24, 25] or makes customization “without penalty” possible [1] because—as it is known—it does not require product-unique equipment and molds, and since the digital redesign of products is not expensive. In additive manufacturing, the degrees of freedom in product creation are exponentially higher than those allowed by conventional production because manufacturing is not limited by the possibilities allowed by subtractive technologies. In other words, additive manufacturing generates products characterized by large freedom and high complexity of geometric features, which are difficult to achieve with conventional technologies.

Ready-made products come out of additive machines, without the need for component assembly, and increasing reliability of products with complex geometries which could be compromised by assembly of components in conventional production. Therefore and ceteris paribus, by avoiding assembly costs, additive manufacturing cuts production costs.

Additive machines can achieve time savings in the creation of pure or tailored customized products: product lead times do not include machine set-up times and component assembly times—despite the generally longer production times of additive machines compared to conventional ones.

Additive machines can also accelerate the time to market of radical and incremental product innovation, thanks to lowering production times of early products, with which to rapidly test and validate product ideas in target markets [20]. Furthermore, additive manufacturing is combined with virtual product prototyping by which to carry out virtual simulation tests, thus eliminating the phase of physical tests which requires time to create prototypes.

Therefore, digitization of manufacturing makes it lean and agile, allowing efficient and fast production on demand of single units or small batches of pure or tailored customized products: that is, additive manufacturing achieves economies of variety.

Additive manufacturing evokes a context of just-in-time production, also generating:

- drastic contraction—up to cut-off—of end-use product and component warehouses and relative costs;

- reduction of warehouses of raw materials and lowering of the relative costs, both for lower consumption of materials per unit of product or component—in fact, these can be made hollow and therefore be lightened—and for less waste of materials compared to subtractive production, thanks to the possibility of reusing waste;

- lowering of manual work in the production processes, thus verifying lower costs of factory staff [2, 21, 22]. Organizational roles, skills, and responsibilities need to be redefined and new knowledge and work skills are required, however more expensive than manual factory ones [8].

In short, additive production verifies a lower dependence on manual work and a greater dependence on skilled work with a high knowledge content, for which it can be said that additive production acts in favor of manufacturing reshoring [26–28].

To all those advantages of additive manufacturing compared to conventional one analyzed so far, we must add the ability of processing materials that cannot be processed with conventional technologies (such as carbon alloys for high temperatures, metal-ceramic, and food composites) or anomalous nature for conventional

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manufacturing (such as organic cells and tissues); longer life cycle of additive product compared to conventional one, thanks to simpler, cheaper, and faster design upgrades that can slow or revitalize the decline of the product in the market.

Lightened additive components—due to the possibility of being made hollow—reduce fuel consumption of additive products (e.g., in the aerospace and aeronautical industries). In this sense, additive manufacturing has been labeled as functional for environmental sustainability.

From the above, it follows that additive manufacturing can generate greater value for the customer and, therefore, a greater willingness to pay a higher price to obtain highly customized products, whose unit production costs and delivery times are lower than those conventional manufacturing would be able to achieve [29].

2.2 Disadvantages of implementing additive manufacturing in conventional manufacturing-based companies

As anticipated, alongside the advantages (pros) of additive manufacturing over conventional manufacturing, there are numerous disadvantages (cons) that must be measured and compared with the aforementioned advantages in trade-off analysis.

First of all, absence of economies of scale of additive machines. In fact, a widespread thesis among scholars is that additive machines would not allow economies of scale because the average unit additive product cost tends to be invariable as production amounts vary.

In our opinion, the reasoning about economies of scale denied by additive technologies is more complex. Total variable costs of additive manufacturing tend to be higher than total fixed ones, but this does not justify the constant average total unit cost of the additive products as production increases. What is undoubted is that additive technologies make it possible to achieve the minimum efficient scale in correspondence with a very low number of units produced. It is known that the minimum efficient scale is high when the level of fixed capital required for production is high. The higher the minimum efficient scale, the smaller the number of firms on the market. This is valid for conventional technology machines, whose minimum efficient scale is reached in correspondence with a large number of products. All this confirms that additive technologies make the level of capital to be invested to do business low. As a result, additive technologies are able to expand the number of smaller efficient production structures present in a territorial context, because the level of fixed capital required to do business tends to be smaller than that required by conventional production.

Therefore, unlike conventional machines, additive ones are efficient in highly customized unit productions or in low-volume ones, and the convenience of using them in manufacturing processes decreases as demand grows up. Persistent limits of additive machines—such as low throughput times and poor quality standardization of products—are the causes that prevent digital manufacturing from achieving economies of scale. Nothing prevents these limits from being exceeded in the near future.

Another disadvantage of additive manufacturing is the non-standardizability quality of additive products and spare parts in terms of strength, durability, consistency, safety, accuracy, and consequent low certainty of reproducibility of products and spare parts [8], which often generates post-processing costs of products and components (e.g., costs of polishing the surface of products) [30]. Lack of shared quality standards makes quality assurance and product warranty difficult.

Disadvantages of additive manufacturing match with advantages in a trade-off evaluation are also difficulties in finding and the high cost of additive materials;

difficulties of their technical integration [26, 31], as well as high prices of additive machines to be used in production cycles.

In additive manufacturing, the hourly cost of subordinate labor tends to be higher than in the conventional one because the former has a higher skill content [31].

Moreover, there is a non-secondary problem of lack of clarity of intellectual and industrial property of additive product designs, which can represent a bottleneck for the implementation of additive technologies.

At last, the high energy consumption of additive manufacturing and material preparation processes must be considered, as well as the size limits of additive components or end-use products caused by the size limits of AM machines [32].

Table 1 shows the summary table of the pros and cons (advantages and disadvantages) of additive manufacturing compared to conventional one.

	Advantages	**Disadvantages**
Costs	• Minimization of investment in equipment • No assembly costs • Less manual work in production processes • Zero end-use product and component warehouses/just-in-time production of products • Lower consumption of materials per product/waste recovery	• Limited availability and high cost of raw materials • High prices of additive machines • Tendentially higher hourly labor cost • Post-processing costs • High energy consumption • Lower economies of scale
Times	• Shorter lead times and time to market • Longer life cycle of additive product for easy upgrade	• Lower throughput time
Flexibility	• Pure or tailored customization without extra cost • Greater creative freedom and complexity of the geometric characteristics of the products	
Quality	• Higher Reliability of products with complex geometries • Possibility of processing materials that cannot be processed with conventional technologies	• Lower shared quality standards and difficulties in the process of quality assurance and guarantee of additive products • Not always guaranteed availability of raw additive materials • Raw materials available are not always able to generate additive products with qualitative characteristics comparable to those of conventional ones • Non-standardizability quality of additive products and components
Price	• Willingness to pay a premium price	
Other		• Poor clarity of intellectual and industrial property of product designs • Dimensional limits of products and machines

Table 1.
Advantages and disadvantages of implementing AM technologies in conventional companies.

3. Implementation of additive technologies in conventional supply chains: AM-based supply chain configurations

3.1 Centralized additive configurations

If shared across multiple organizations, value creation occurs in a supply chain, which is the value system that integrates intra-organizational value chains.

The implementation of additive manufacturing technologies in conventional technology supply chains generates different AM-based supply chain configurations, depending on the supply chain strategy pursued by the focal company (manufacturer). Therefore, as a guideline in the field of supply chain management, it is suggested to design the AM-based supply chain setup according to the supply chain strategy chosen by the focal company. In other words, the AM-based supply chain setup should be designed to implement the chosen supply chain.

The adoption of additive manufacturing in conventional supply chains, in fact, implements not only and not always product customization strategies, but always occurs at the individual company level, but often cost optimization supply chain strategies.

The supply chain strategy determines the level of the supply chain affected by the implementation of additive technologies: the lower the level of the supply chain affected by the implementation of additive technology, the greater the customization of the product guaranteed to the customer, the faster the delivery time, but the lower the cost savings. Thus, it can be argued that supply chain strategies determine its basic configurations, which are as follows:

- centralized additive configurations, whether additive technologies are implemented in OEM plants for the production of components and products, or in regional distribution centers that produce spare parts on request from local service centers, using the spare part designs provided by the OEM. In this case, the spare parts are delivered to the local service centers before being used for the repair and maintenance of the installed base, that is, the local manufacturing plants [33, 34];

- fully decentralized or distributed additive configurations, whether additive technologies are implemented in production plants close to clients or in service centers close to installed bases;

- hub additive configurations, which are intermediate structures between totally centralized configurations and totally distributed ones, with intermediate locations of additive technologies, that is, between the main plant and local production centers (or service centers, in the case of spare part supply chains) close to customers [6].

AM machines centrally located in a supply chain typically eliminate inventory of components and spare parts that are infrequently or occasionally required by internal and external customers (low-demand products or products with large peaks and drops in demand) and whose response time to demand is not critical [12, 31]. In other words, the central warehouse of components or spare parts of this type is replaced by centralized production capacity and inventory of materials and 3D files for additive manufacturing [28]. The costs of storing raw materials and files for additive manufacturing are lower than those of components with large peaks and dips in demand, so the overall inventory packing and storage costs of centralized AM-based supply chains are likely to be lower than those of conventional supply chains.

	Advantages	Disadvantages
Costs	• Reduced stock-keeping and packaging costs for components, products, and spare parts with fluctuating and unpredictable demand	• Higher centralized fixed costs for investments in additive machines • Higher costs of raw material warehouses • High energy costs
Customization	• Higher degree of customization of the component without extra-costs	
Risks	• Lower risk of stock-out of safety components and spare parts	
Times		• Slower component throughput-times

Table 2.
Centralized additive configurations.

The presence of a centralized additive production capacity reduces the risk of stock-out of safety components and spare parts and increases the possibility of their customization.

On the other hand, costs for fixed investments and the dependence of the supply chain on suppliers of raw materials are growing. The costs of additive machines are high as well as energy consumption, while the impact of additive technologies on the total transport costs of the supply chain must be measured and evaluated according to the specific contextual situation.

Below is a synthesis of the analysis so far (**Table 2**).

3.2 Decentralized additive configurations

Implementation of additive technologies in production facilities close to places where end-use products are used, that is, close to the external or internal customers, draw AM-based decentralized supply chains and support product customization strategies. Bypassing component suppliers and end-use product distributors, AM-based decentralized configurations reduce the number of tiers in the supply chain Therefore, they embody the disintermediation of the supply chains, generating reductions in logistics costs, however in the face of the multiplication of local investments in the supply chain which must therefore be justified by local demands to be met in a specific way and in a short time.

In a nutshell, investments in decentralized additive machines increase the fixed production costs of the supply chain and lower the costs that depend on the logistic levels (e.g., transport costs, warehouse costs).

The lower total stock-keeping costs of AM-based decentralized supply chains, compared to traditional ones, are determined despite the greater presence of inventories of raw materials, often in the form of powders or liquids, instead of inventories of components and sub-assemblies, which are bulkier and more expensive than materials. It follows that whether on the one hand, it is possible to observe a minimum dependence of the decentralized supply chains on the suppliers of components, on the other hand, a greater dependence of the same supply chains on the suppliers of additive raw materials is generated.

Decentralized supply chains based on additive technologies tend to guarantee shorter delivery times of products compared to centralized ones, as a consequence not only of the reduction of logistic tiers, but also of the proximity of AM machines to end users of products or spare parts. Furthermore, it should be considered that, in decentralized AM-based supply, the decrease in transport costs is determined not only by the disintermediation of the supply chains (the decrease in the number of tiers) and by the proximity of the AM machines to the end customers, but also by the object itself of the transport (raw material rather than components and end-use products.)

As a result, the risks of transport damage to components and products are reduced.

Coeteris paribus, by reducing transport and realizing manufacturing in situ, disintermediation of supply chains guarantees lower consumption of fossil fuels and lower carbon dioxide emissions.

Although additive machines consume electricity to a large extent, the total balance in terms of environmental sustainability of AM-based supply chains is proven as tendentially positive by numerous studies—also thanks to the lower weight of vehicles (aircrafts and cars) that have hollow and light components.

Decentralized AM-based supply chains serving the plurality of local markets have also been defined as mini-factory networks [14, 35]. Mini-factories are local production facilities close to the end customers. Additive manufacturing technologies, with which each mini-factory is equipped, reduce customization costs. In addition to production activities, each mini-factory carries out sales and customer assistance, often also digital product design activities. Networks of mini-factories are enterprises of pure and tailored customization [13]. Proximity of the mini-factory to the customer or a local market allows the focal company della supply chain to access customer knowledge which is highly strategic for the purpose of creating customized or highly customer-specific products, but also for innovative processes.

By favoring short delivery times and low costs of production of personalized or unique products, mini-factories embody lean agile factory principles.

As aforementioned, the decision to invest in distributed AM machines—which are expensive at the current stage of development that additive technologies have reached—must be economically justified by the existence of local demands, even if low and fluctuating, which must be satisfied in a personalized way and in a short time, as in the case of spare parts requested in aeronautics or biomedical sectors (heart valves, prostheses, dental implants) [9, 26] or be motivated by demands from places difficult to reach by conventional means of transportation [9, 24, 36]: so, additive manufacturing is certainly the enabling technology of space economy.

The decentralized implementation of digital additive manufacturing technologies in a supply chain implies the replacement (total or partial) of warehouses of components and sub-assembly systems, spare parts, and end-use products, not only with warehouses of raw materials, but also with "virtual warehouses" of digital design files. Raw materials and design files travel faster and more efficiently than physical materials, components and products, along supply chain tiers—the latter reduced in number—and no specific local knowledge is required for on-site production: designs submitted to decentralized production structures through IT infrastructures, incorporate necessary knowledge for product realization. Therefore, as a precondition, implementation of additive technologies in decentralized supply chains requires huge investments in ICT infrastructure, capable of supporting the production and circulation of knowledge incorporated in designs in supply chains themselves. In fact, the lack or weakness of ICT infrastructure of a supply chain is to be considered bottleneck, which hinders the implementation of additive technologies [23].

	Advantages	Disadvantages
Costs	• Lower transport costs • Lower stock-keeping costs • Lower consumption of fossil fuels and lower carbon dioxide emissions = lower environmental impact of manufacturing production	• Multiplication of fixed costs • High costs of additive machines • More investments in IT infrastructures
Customization	• High customization of single units or small batches without extra costs • Access to customer knowledge	
Times	• Shorter delivery times	
Competences	• No specific local competence required for on-site production/ability to produce in hard-to-reach places	
Risks	• Lower dependence on component suppliers • Lower risk of stock-out of components and spare parts • Lower risks of transportation damage to products	• Increased dependence on raw materials for AM suppliers

Table 3.
Decentralized additive configurations.

Additive manufacturing also requires customer digital design knowledge and skills: to be made on demand, that is, according to customer-specific requests, additive products must be designed on the basis of co-design platforms that carry out co-creation of value with customer.

Therefore, a first summary can be drawn from the analysis carried out so far: additive technologies centrally located in a supply chain generally reduce the costs of central component or spare parts warehouses whose response times to demand are not critical, replacing them with fixed investments in machines additive and with warehouses of raw materials and 3D files for additive manufacturing; decentralized additive technologies lower the number of supply chain levels, and therefore all those costs that depend on that number (e.g., transport costs and warehouse costs of the entire supply chain). It can be said that the lower the level of supply chain affected by additive technology implementation, the greater product customization guaranteed to the customer, but the lower cost savings ensured.

Table 3 shows the summary of the pros and cons of decentralized AM-based supply chains versus conventional ones, based on the analysis so far.

3.3 Hub additive configurations

In between the two aforementioned structural configurations are hub configurations.

In logistics, the concept of supply hub is well-established in conventional manufacturing [17]. From the point of view of conventional technology supply chains, the concept of hub refers to supply of components or sub-assemblies to local production plants. Hub functions as a buffer of components for the manufacturing plants in a just-in-time context [6, 17, 37]. In fact, the purpose of supply hub is to satisfy downstream demand in a timely and regular manner, and this occurs both thanks to its proximity to the main plant and by assembling parts purchased from upstream suppliers into sub-assemblies to send downstream [38]. Therefore, the use of a supply hub reduces supply risks and investments in equipment and labor of the entire supply chain compared with structural solutions that involve the direct supply of components from external suppliers. As a result, the complexity of operations at the supply chain level is reduced.

In a nutshell, in multilevel supply chains, a consolidation hub enables smooth and reliable supply of components or sub-assemblies to manufacturing plants and lowering structural costs. All this fosters transition of manufacturing in a just-in-time (JIT) context [37].

Supply hub can belong to one supply chain or serves multiple ones. In the latter case, higher volumes of off-the-shelf components purchased and high production volumes of sub-assemblies supplied to local locations, greatly reduce end-use product unit costs.

In an additive manufacturing context, hub configuration refers to an intermediate supply chain structure between fully centralized configuration and fully distributed one. Hub's AM machines are located in a logistic tier between the main plant and local manufacturing plants. They are oriented toward the realization of various strategic objectives, some of which are pursued by AM-based centralized supply chains, others by decentralized ones.

Therefore hub configuration has some of the main advantages of a centralized manufacturing supply chain configuration (e.g., it requires fewer machines and less manpower to meet total demand than a decentralized supply chain configuration, and thus guarantees better utilization of production capacity), but also some advantages of decentralized configuration compared to the centralized one (lower transport costs and faster, cheaper and smoothly supplies) [2].

4. The decision-making process for the implementation of additive technologies in conventional structures: method guidelines

Distributed or decentralized AM-based supply chains are likely to be more concise than traditional ones—and also than centralized AM-based ones: they cut off component suppliers and distributors, but become more dependent on raw material suppliers. It is known that raw materials for additive manufacturing are expensive, but generate lower inventory costs than the components and end-use products ones. Raw material costs are variable production costs; instead, component, spare part, and product costs include fixed costs. Because decentralized AM-based supply chains have fewer layers than conventional ones, and centralized AM-based ones, the transportation costs of the former are likely to be lower than the latter.

All things being equal, in AM-based supply chains variable production costs are higher than in conventional ones, due to material and labor costs, assessed by Li et al. [31] as higher than those incurred by a supply chain based on subtractive technology. In fact, as anticipated in the previous pages, additive technologies generate a change in the required work roles: less manual work, less knowledge related to machines, but new design and operational roles, generally more expensive than the manual ones of subtractive production.

As regards fixed costs of production, Li et al [31] point out that supply chains based on additive technologies may not be cost-effective compared to those based on conventional technologies: costs of AM machines are still high today and multiply in the case of distributed production.

In our opinion, it should also be considered that additive machines undergo rapid obsolescence due to the acceleration of technological innovation in this field of application, so the incidence of fixed costs on additive product unit cost tends to be more high a fortiori.

Based on what has been described in the previous paragraphs, it can be argued that, although additive manufacturing has many advantages over the conventional one, this is not enough to support the superiority of AM-based companies or supply chains over conventional ones in any business situation and environmental context. In fact, on the basis of the analysis so far, it can be noticed that there are negative quantitative interactions between pros and cons of additive manufacturing, that make AM-based company or supply chain not always feasible or appropriate.

All this for saying that the advantages and disadvantages of implementing additive technologies in conventional companies or supply chains have to be measured ex-ante and assessed in trade-off to decide about additive manufacturing choice.

As guidelines of company or supply chain management, in order to design a decision-making process for the implementation of additive technologies in organizational structures based on conventional technologies, a number of decisions are suggested: firstly, which method of simulation of company or supply chain based on additive manufacturing to adopt, then which specific additive technology to implement. With regards to supply chains, the focal company also has to decide at which level of the supply chain to implement additive manufacturing, that is, which AM-based supply chain configuration to adopt. In the previous pages, we have argued that the logistical level of the conventional supply chain affected by the implementation of additive technologies depends on the supply chain strategy decided by the focal company, in other words, the configuration of the AM-based supply chain that comes about depends on the chosen supply chain strategy.

The decision-making process for the implementation of additive technologies in conventional companies or supply chains always requires the choice of a simulation method on the basis of which to build AM-based company or supply chain models from which to derive cost functions to be compared with those of the status quo. The comparison between the aforementioned cost functions substantiates the ex-ante and trade-off assessment of the advantages and disadvantages of the additive option. Furthermore, the decision-making process described up to now must be repeated for all the different and possible additive technologies that can be adopted, because the effects that each of them can produce on conventional companies or supply chains can be so different as to imply different decisions.

In another study of ours [21], we specified that only a small number of scholars deal with the evaluation of the pros and cons of the implementation of AM from a quantitative point of view, thus filling a gap present in the studies on additive technologies. Among them are Li et al. [31], who suggest that the choice of one supply chain configuration can only be taken by resorting to mathematical simulation models of supply chains from which to derive functions of quantitative variables to be compared, mainly cost functions.

5. Conclusions

5.1 Recent advances

- Centralized implementation of additive technologies in a conventional supply chain lightens and simplifies its structure without changing the number of logistic tiers (component supplier-manufacturer-distributor-customer), because it reduces the intervention of suppliers of components and spare parts required fluctuating and in small quantities by the manufacturer. The result is reduced inventory costs, as centralized additive machines reduce the risk of stock-out of discontinuously requested, low-quantity spare parts and components. In a centralized AM-based supply chain, inventory costs are therefore likely to be lower than in a conventional one, although they are partly replaced by AM machine costs. Product customization is allowed not only by the assembly of modules but also by the potential of additive machines. The production context is that of modularity. Balance between the advantages and disadvantages of a centralized additive choice has to be measured to decide on its implementation.

- Distributed or decentralized AM-based supply chains are likely to be more concise than traditional ones and centralized AM-based ones: they cut off component suppliers and distributors, but become more dependent on raw material suppliers. It is known that raw materials for additive manufacturing are expensive, but generate lower inventory costs than the components and end-use products ones. Raw material costs are variable production costs; instead, component and product costs include fixed costs. The customization of the product is made possible by the large geometric freedoms with which the product can be made, allowed by the additive machine near the customer. So the production context is that of pure customization. Since decentralized AM-based supply chains have fewer levels than conventional ones, as well as centralized AM-based supply chains, any cost dependent on those levels (i.e., transportation cost) is likely to be lower in the former than in the latter. Balance between the advantages and disadvantages of a decentralized additive choice has to be measured to decide on its implementation as well.

- No AM-based supply chain configuration is better than the other because the advantages and disadvantages of each, inferred from simulation models, must be measured quantitatively and weighed in trade-off assessments. Thus, in certain organizational and environmental contexts, conventional supply chains can be better than additive configurations.

Referring to Verboeket and Krikke [23], we specify that the replacement of the central warehouse with centralized additive machines can represent a first step in the process of implementing additive technologies in supply chains and that, over time, a configuration centralized AM can evolve into a distributed one.

5.2 Future directions

The development of additive manufacturing technologies is moving toward the maturity stage, therefore, a rapid improvement in the technical characteristics of additive machines on which economies of scale depend, such as throughput time and standardization of production, is likely.

As a result, an increasingly vast adoption of additive machines in companies and supply chains is foreseeable, accompanied by a progressive decrease in prices.

Nowadays the consumer increasingly wants to participate in the business process of value creation, postulating personalization, short delivery times, and, at the same time, convenient prices. Additive technologies allow for the most suitable product solution for this market context.

The near future is a complete outsourcing of the production process to the consumer. So, distributed manufacturing can be considered an intermediate stage in the evolutionary process of manufacturing toward pure customized production made directly by the consumer, using design files downloaded from open design platforms, and by home printers or nearby 3D printing shops [39].

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