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# Smart Additive Manufacturing: The Path to the Digital Value Chain

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**Abstract:** The aim of this article is to characterize the impacts of Smart Additive Manufacturing (SAM) on industrial production, digital supply chains (DSCs) and corresponding digital value chains (DVCs), logistics and inventory management. The method used consists of a critical review of the literature, enriched by the authors' field experience. The results show that digital transformation of manufacturing is affecting business models, from resource acquisition to the end user. Smart manufacturing is considered a successful improvement introduced by Industry 4.0. Additive Manufacturing (AM) plays a crucial role in this digital transformation, changing the way manufacturers think about the entire lifecycle of a product. SAM combines AM in a smart factory environment. SAM reduces the complexity of DSCs and contributes to a more flexible approach to logistics and inventory management. It has also spurred the growth and popularization of customized mass production as well as decentralized manufacturing, rapid prototyping, unprecedented flexibility in product design, production and delivery, and resource efficiency and sustainability. SAM technology impacts all five Fletcher's stages in DVCs. However, the need for clear definitions and regulations on 3D printing of digital files and their reproduction, as well as product health, safety, and integrity issues, cannot be ignored. Furthermore, investment in this technology is still expensive and can be prohibitive for many companies, namely SMEs.

**Keywords:** Industry 4.0; smart additive manufacturing; logistics; inventory management; digital supply chains; digital value chains



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## 1. Introduction

This study examines the implications of smart additive manufacturing (SAM), or smart three-dimensional (3D) printing, for industrial production logistics and inventory management as well as for digital supply chains (DSCs) and digital value chains (DVCs) within the context of Industry 4.0.

The fourth industrial revolution, often referred to as “Industry 4.0”, has ushered in new digital technologies and more digitization and automation of the manufacturing environment, all of which require companies to adopt manufacturing technologies that support machine-to-machine and human-to-machine communication in a virtual environment if they want to continue being competitive in the market [1]. Digital technologies, such as artificial intelligence (AI) and SAM, allow the interconnection of all elements related to manufacturing processes through advanced digitization, such as the integration of the Internet and intelligent objects (machines and products). The connection between the physical world and the digital factory creates a “cyber physical system”, which has also been referred to as the “smart factory”, “digital factory”, “smart manufacturing”, “smart firm”, “industrial internet”, or “integrated industry” [2]. The arrival of Industry 4.0 has made digitally supported production the center of attention, allowing for faster manufacturing and more customization than ever before. As a result, the emergence of new digital

technologies and novel business models are accelerating an industry transformation that impacts current business methods and even the structure of the market [3].

This new digital industrial paradigm is also having a major impact on the digitization of production logistics applications, inventory management, supply chains (SCs), and value chains (VCs). As a result, new terms such as “digital inventory”, “digital supply chains” (DSCs) and “digital value chains” (DVCs) have been coined to identify the swift evolution required by Industry 4.0 [4].

Additive manufacturing (AM) has always been at the forefront of technological advances and has been a target of research efforts to leverage its capabilities and accelerate digital transformation in the manufacturing sector. AM increases the digital interaction with customers, and it allows manufacturers to print on site quickly, customize mass production, and proceed to direct manufacturing while reducing waste, shipping costs, and delivery time. It can also reduce the complexity of SCs [5].

Within this context, SAM has emerged, which combines AM with intelligent or smart technologies, devices, and systems. Given the speed and growth catalyzed by Industry 4.0, it is crucial to examine the contributions and advantages, as well as the risks and challenges, involved as SAM becomes an integral part of DSCs and, ultimately, in DVCs.

One of the most promising research topics focuses on the relationship among the emerging key enabling technologies of Industry 4.0 (e.g., SAM) and production logistics and inventory management, DSCs, and DVCs [6]. The influence of AM technology on production logistics and inventory management, SCs, and VCs is undeniable, so it is vital to understand the fundamentals and the potential effects of SAM on the manufacturing industry.

This study presents a critical review exploring the most current research and advancements to date on the impacts of SAM on the manufacturing sector. Section 2 introduces digital manufacturing, DSCs, and DVCs. Then, smart manufacturing and SAM are presented in Section 3. Section 4 presents and discusses the results of our research, specifically on the links between SAM, production logistics and inventory management, DSCs, and DVCs. Finally, Section 5 summarizes the main findings of our research.

## 2. Digital Manufacturing, Digital Supply Chains, and Digital Value Chains

Digital transformation is affecting business models from resource acquisition to end user delivery. New technologies such as AI, Big Data, and Data Analytics, the Internet of Things (IoT), Augmented Reality (AR), Cloud Computing, AM, Robotics, and Autonomous Vehicles are redesigning every link in the supply chain by automating and modernizing entire workflows [7]. In this context, some studies analyze the impact of these technologies on supply chain management and logistics. With regard, for example, to the relationships between AM and AR, they indicate that these technological tools can support existing processes and activities in the value chain, from design and planning, training of human resources, inbound logistics, production operations, even logistics of sales and billboard [8]. One example is the application of smart glasses in advanced logistics and production environments, creating opportunities to develop and evaluate innovative solutions for work assistance, efficiency, satisfaction, and safety [9]. Other examples cited in the literature show how, combined, AR and AM may impact SCs:

- (a) AR can improve the fabrication speed in a SAM process, through the communication of the layout information between a reconfigurable AM system made of robotic arms and its corresponding digital twin for toolpath planning and simulation, allowing the introduction of multiple independent actuators for concurrent deposition of materials without collision among them [10].
- (b) AR can also support the detection of problems in an AM process caused by inaccessible measurements or parts movements that are difficult to anticipate, through an AR-based application that allows evaluating individually engineered parts based on virtual three-dimensional (3D)-computer-aided design models (CAD) projected to the intended installation-site [11].

When entrepreneurs decide to adopt digital transformation processes, they likely have several goals in mind, but perhaps one of the most visible and important goals is the reduction of time to market. After all, time is their most precious asset, both today and in the future. Therefore, bringing solutions to market faster than the competition constitutes a substantial advantage [12].

The adoption and the incorporation of digital manufacturing technologies have been responsible for the paradigm shift in the industry, and the speed at which they can be implemented has had a tremendous impact on competitiveness. Organizational and environmental contexts can influence how quickly, and efficiently new technology can be implemented. However, the impact can be mediated by the technological ability and the maturity of the company. In addition, the integration of these digital technologies also can have a significant impact on a company's performance (i.e., flexibility, design, delivery, and quality) [13,14].

The concept of digital transformation has consequently become a deeply debated topic within academic discourse in recent years, commonly associated with Industry 4.0 and its new industrial paradigm [15–17]. However, in this changing world, competition is no longer just between companies; it is now also a concern for the supply chains involved [18].

According to Lee and Billington [19], “the supply chain is a network of producers and distributors that supply raw materials, convert them into intermediate goods and final products, and distribute final products to customers”. SCs and production logistics play a crucial role in global development [20]. Rapid changes in different markets and in economic, financial, social, and technological aspects result in dynamic SCs characterized by constant evolution. To remain competitive in the industry, SCs (and corresponding VCs) must also change in size, shape, and configuration as well as in the ways they are coordinated, controlled, and managed [21].

More recently, the logistics and management of global SCs have gained special importance and public interest, as a result of the COVID-19 pandemic crisis, which has been responsible for severe restrictions on the production, transportation, and distribution of goods [22–24]. In this context, an efficient management of SCs proved to be essential both in terms of controlling the spread of the pandemic and guaranteeing the supply of essential goods [25,26]. Digital technologies have emerged in this context as a tool to overcome the challenges, with emphasis on Virtual Reality, AR, holography, 3D scanning, AM or 3D printing and Biosensor [27].

At this point, digital transformation is crucial, as it increases the connection between supply chain members and allows SCs to be managed more efficiently, giving rise to DSCs and corresponding DVCs. As DSCs achieve more advanced automation and integration between their systems, the machines and equipment in production are coordinated via the Internet and smart sensors, and all the data generated in this process are stored in the cloud [18].

However, the digital transformation strategy involves not only evaluating and identifying the technologies to be applied, but also the capacities, competencies, business models, and even the organizational structure that must be adapted for this transformation. Furthermore, to be successful, managers, employees, and all supply chain participants must adopt new practices [28] and a new culture.

Before starting the transformation, though, it is necessary to create a roadmap aligned with the upcoming challenges. Company managers must assess potential difficulties before and after digital transformation [12]. In exchange, digital transformation will allow them to continuously monitor raw materials and evaluate the supply and the availability of the machines needed so they can make efficient adjustments and more accurate predictions across their manufacturing processes.

In summary, digital transformation is a strategic decision for companies and the SCs in which they operate. Throughout the process, companies, namely Small- and Medium-sized Enterprises (SMEs), face financial, cultural, legal, technical, and implementation difficulties [29]. To survive in a competitive environment, they must adopt a digital trans-

formation strategy combined with a culture of innovation while assessing and planning for the inherent challenges and risks [30].

### 3. Smart Manufacturing, Additive Manufacturing, and Smart Additive Manufacturing

#### 3.1. Smart Manufacturing

Traditional manufacturing processes involve multiple steps that are not always integrated (e.g., molding, heat treatment, milling, grinding, etc.). In contrast, smart manufacturing is a technology-driven approach that uses a fully integrated and collaborative manufacturing system that allows companies to monitor production processes and react in real time to meet the dynamic demands and conditions of factories, SCs, and customer requirements. This system involves the installation of smart sensors in manufacturing machines that collect data on the machine's operational status and performance. The data are then analyzed to identify opportunities to adapt and improve manufacturing performance [31].

Smart manufacturing involves a new generation of production systems that comprise advanced technologies, such as machinery connected to the Internet, to monitor the production process and improve its performance [32]. A smart factory must include not only automation but also human-machine collaboration that together will improve operational efficiency [33]. As the IoT is integrated into more machinery and networks, greater levels of automation can be achieved. However, in addition to the IoT, other technologies play an essential role in smart manufacturing, which include AI, machine learning, edge computing, predictive analytics, and digital twins [34].

Smart manufacturing has been considered a successful improvement introduced by Industry 4.0 and improving resource efficiency and adaptability. Its broad application of the Internet and innovative engineering technologies has helped to integrate customer and business value processes and create a better manufacturing environment [35]. This smart approach offers several benefits to companies, including greater efficiency, greater productivity, and long-term cost savings. It improves their market competitiveness by optimizing the use of labor, energy, and materials in the production of high quality, customizable products and improving response times to variations in market demand as well as reducing delivery time. Moreover, in terms of efficiency, one of the main savings comes from the reduction of production stoppages. Modern machines are often equipped with remote sensors and diagnostics to alert operators to problems as they occur. Predictive AI technology can highlight problems before they occur and enact steps to mitigate them, which in turn reduces their impact on cost and efficiency [36].

Kusiak [31] identifies the six pillars associated with a smart manufacturing environment:

- (a) Pillar 1—The emergence of manufacturing technology and processes: AM is an example of a new technology that has inspired the development of new materials, impacted the design and the manufacture of products, and opened doors to new applications.
- (b) Pillar 2—Materials: Smart manufacturing is open to all types of materials including organic-based materials and biomaterials. However, the emergence of new materials requires their incorporation into smart manufacturing and the development of new processes.
- (c) Pillar 3—Data: We are witnessing a significant increase in data collected from various sources, some of which have been triggered by the deployment of smart sensors, wireless technologies, and data analysis. The data will be used to shape the development of future programs and applications as well as in building predictive models.
- (d) Pillar 4—Predictive engineering: Predictive engineering creates high-fidelity digital models of the phenomena of interest, which will inform decisions about future production and market conditions.
- (e) Pillar 5—Sustainability: The development of products and processes should be guided by a sustainability criterion including sustainable product design, manufacturing processes, and materials.

- (f) Pillar 6—Resource sharing and networking: As manufacturing engages more digital and virtual technologies, many of the creative and decision-making activities will require resource sharing and networking.

### 3.2. Additive Manufacturing

Commonly referred to as 3D printing, AM is a “technology that applies the additive-shaping principle and therefore builds physical 3D geometries by successive addition of material” [36]. Since its invention in 1986 by Charles Hull (founder of the stereolithography process), it has gained significant academic and industrial interest due to its ability to create complex and customizable structures [37].

According to the literature, AM technology is responsible for a revolution in the way products are designed, manufactured, and supplied to end users. For example, in 2020, it played a key role in combating the spread of COVID-19 by providing custom parts locally on demand, reducing waste and transportation costs, eliminating the need for an extensive manufacturing pipeline in the production of face shields, palliative face masks, cotton swabs, hands-free door openers, quarantine booths, etc. [38–41].

Although no longer a novelty, AM technology continues to revolutionize industries, in terms of technology as well as materials and processes used [42]. The European Association of Machine Tool Industries and Related Manufacturing Technologies [43] associates AM technology with the following four principles:

- (a) Principle 1—Innovation: AM technology promotes the creation of new business models based on localized production, mass production customization, and/or the diversification of products and services.
- (b) Principle 2—Performance: AM technology enables the creation of parts with optimized material distribution, resulting in better performance.
- (c) Principle 3—Sustainability: AM technology can produce parts using recycled materials or materials that are reintroduced into the production process. For this reason, this technology facilitates a circular economy by minimizing the ecological footprint. In addition, lighter and more durable products are created with this technology, as compared to production using conventional technologies. It also supports reduced fuel costs and emissions, namely in activities and sectors linked to mobility.
- (d) Principle 4—Competitiveness: AM technology reduces the time to market as it reduces the time between conception and production and allows production to be decentralized (i.e., the end product can be produced at multiple locations rather than from a single factory or plant, reducing transportation costs).

Therefore, AM technology has the potential to reduce development, production, and transportation costs as well as increase product performance [44], sustainability and competitiveness.

The benefits of AM technology attracted much attention in the field of manufacturing for applications such as custom mass production, prototype creation, and sustainable production, all while minimizing the time (product development/design) and the costs involved.

Recently, new developments in AM processes, technologies, and applications, have made it more appealing, such as bioprinting, four-dimensional (4D) printing, nanoscale printing, and metamaterial printing [45–49].

4D printing is one of the most recent achievements in AM technologies and has attracted considerable attention in academic and industrial circles since 2013, although commercialization still requires additional research and development [50]. Known as the fabrication of a complex spontaneous structure that changes over time, intentionally responding to external stimuli, 4D printing has its origins in 3D printing, but goes beyond 3D printing, as manufactured objects are no longer static and can be transformed into complex structures by changing size, shape, other properties, and functionality, making 3D printing alive [51,52]. These techniques have been applied in the field of flexible robots, grippers,

and tissue engineering. The materials used are known as smart materials or programmable materials, highly dynamic in form and function, responding to external stimuli [53,54].

As AM technologies mature and knowledge associated with smart materials, available stimuli, mathematical modeling and geometric programming increases, several studies highlight the need for additional research on computer-aided design software to be able to visualize the properties of smart materials in conjunction with the use of physical simulation at multiple scales. Again, this implies combining AM with AR. On the other hand, manufacturing systems must be sufficiently reliable to ensure that the spacing between the voxels that represent the materials is adequate and reproducible, and it is also important that new metrology equipment or other forms of measurement be developed to ensure the quality of parts [55]. With the integration of AM technology into production processes, companies have experienced a higher degree of flexibility and agility when changing production schedules and places, which in turn has allowed for the better use of resources and raw materials, leading to a reduction in operational costs. Another advantage of this technology is the significant reduction of time in product design and manufacturing, and the reduction in the delivery time of the product to the end user, both of which greatly improve competitiveness for any manufacturer [56,57].

When looking at the effects of AM on SCs, the literature identifies seven potential effects [56,58–61]:

- (a) Effect 1—Reduction in supply chain complexity: AM technology can often produce a complete unit, eliminating the need to assemble multiple components. It also reduces the need for replacement parts, shortens the flow of production, allows for better monitoring of the materials used, and reduces internal production costs (e.g., internal transport, labor, etc.).
- (b) Effect 2—Flexible logistics and inventory management: The integration of AM technology can significantly influence logistics and transportation activities and, consequently, global value chains since production can take place close to the final consumption location. This can reduce costs on several fronts, including configuration and reprocessing, inventories, spare parts, and other associated costs, including transportation costs. We may be facing a new trend in manufacturing that is focused on replacing physical products and raw material stock with digital stock stored in a 3D file format.
- (c) Effect 3—Mass customization: AM technology has encouraged mass (production) customization, as opposed to mass production, as it facilitates the production of customizable products and design flexibility at a reasonable cost while being environmentally responsible.
- (d) Effect 4—Decentralization of manufacturing: AM technology can bring several benefits to global supply chains, such as on-site production and consumption. This can shorten the response time to changes in demand and reduce overall time to market.
- (e) Effect 5—Design freedom and rapid prototyping: AM technology enables the production of parts with complex geometries, overcoming some of the restrictions associated with product design, such as higher costs when using traditional subtractive processes. In turn, this technology is associated with a new era in global production through the digitization of production, where a wide range of fundamentally different items can be made, quickly and easily, according to end users' specifications.
- (f) Effect 6—Resource efficiency and sustainability: AM processes generally consume less energy compared to conventional manufacturing processes. On the other hand, the reconfiguration of shorter, more collaborative supply chains extends the life of a product via repair, remanufacturing, and reconditioning.
- (g) Effect 7—Discussions surrounding regulations, safety, and security: The current legal framework for AM or 3D printing does not regulate the digitization of physical objects. Therefore, the proliferation of digital files containing physical scanned products is not adequately monitored or regulated at this time. In addition, given the vast range

of goods that can be 3D printed, guidelines and regulations regarding safety and intellectual property rights are essential.

When comparing AM technology with traditional manufacturing methods, the greater the complexity or customization required, the more appropriate is the use of AM technology. However, considering current cost models, for large production volumes it can be still more appropriate for some companies to opt for traditional manufacturing methods. Although AM machines offer production flexibility, they require a considerably expensive investment relative to traditional manufacturing machines [62].

There is also a health and safety issue when the material used is powdered, requiring careful design optimization to determine how the powdery residues can be extracted. To lose dust inside a part does not just pose a health and safety issue, it also impacts its mechanical and structural integrity [63]. The wide variety of materials and differentiation in the manufacturing process have resulted in multifaceted quality requirements and standards, which poses problems in terms of quality assurance, accuracy, and reliability [64]. For AM to penetrate a wider commercial market in the future, it is important to invest in a high process stability, a database containing AM material properties, online quality control processes, continuous certification, and provision of rules of design [62].

In a study carried out in 2019, as part of a project financed by the European Regional Development Fund (Grant Number: POCI-02-0853-FEDER-000041), testimonies were collected from Portuguese metalworking companies that had adopted AM technology. One of the companies, which made cutlery, used AM technology to evaluate and validate prototypes after collaborating on designs with their customers [65]. Another company, which produced hospital equipment, declared that: “The use of additive manufacturing technology (3D printing) in the creative and production process allowed, above all, to introduce significant improvements in the design and manufacture of some components.” Specifically, their production involved concept studies that informed the testing and application of components as well as the development of a digital interface for some devices. The increased number of iterations in the manufacturing process accelerated the time to market (through the 3D printing of prototypes) and, consequently, reduced manufacturing risks and issues in various phases of production. In short, the introduction of AM technology allowed internal improvements through the redesign and the creation of new components as well reduced setup time, time to market, and transformation costs (human and material resources). It also encouraged the company to reconsider its production process and storage and logistics issues so they could better plan for a future of bespoke digital production.

AM technology offers unprecedented flexibility in product design, production, and delivery, and, therefore, has the potential to revolutionize strategically important sectors of the manufacturing industry.

### 3.3. Smart Additive Manufacturing

In addition to the previous points, AM technology can be a vital component of smart manufacturing due to its (i) high capacity for mass production customization; (ii) numerous benefits, such as time and material savings, rapid prototyping, high efficiency, and decentralized production; and (iii) networking potential including the possibility of managing an unlimited number of machines simultaneously from a single computer.

SAM is defined as “a fully integrated, collaborative additive manufacturing system that responds in real time to support ubiquitous and intelligent design, manufacturing, and services of 3D printed products” [66]. Given this definition and the integration of SAM and smart manufacturing, it is possible to identify at least two types of “smart” developments related to SAM technology:

- (a) Smart Materials. SAM technology played a key role in recent developments of smart materials associated, for example, with 4D printing [67,68].
- (b) Smart Processes. SAM technology improves smart processes. For example, it facilitates communication between smart 3D printing machines and other equipment in

a factory. In addition, if a problem occurs with production, the collected data will highlight the issue and machines involved, and then AI support can be dispatched to resolve the problem. This allows for flexible and adaptable production systems [69].

SAM technology supports the integration of AM technology in smart factories by expediting communication between devices and employing solutions to resolve critical issues as well as by enabling the application of smart materials. It plays a crucial role in increasing the production efficiency of smart factories.

#### 4. Smart Additive Manufacturing and Digital Value Chains

The technological trends associated with the fourth industrial revolution are prompting the digitization of the value chain [70–74]. Within this context, the whole structure, including the processes, the management components, and the SCs' flows, is changing because of emergent markets that demand customized solutions and quick response and production times. By adding the smart component, we have a fully integrated, collaborative cyber physical system (CPS) that can connect 3D printing machines and other equipment and respond in real time to market demands.

In this context, some studies show that several industries, from aerospace to consumer goods, are investigating the potential of SAM to enable the digital value chain [75]. In the military domain, the potential of SAM for spare parts management and maintenance during field deployments is emphasized, as well as on the responsiveness, efficiency and especially sustainability of the spare parts supply chain [76,77]. In the aerospace industry, the production of critical spare parts also offers economic value; however, the high costs of certification currently make it difficult to further explore this application. Another industry where more research is needed is pharmaceuticals, with a focus on possible personalized drug delivery systems [78,79]. More recently, we have seen important changes associated with the impacts of SAM on DSCs and correspond DVCs, resulting from the COVID-19 pandemic. SAM technology has shown its capability of providing better digital solutions for daily lives during this pandemic crisis. Namely it has supported the effective printing of several and especially designed Personal Protective Equipment (PPE) relevant to fight the COVID-19 pandemic, with less stress, time, and material usage. In addition, SAM has provided an automated solution for various manufacturing industries and other related fields to produce medical equipment during the pandemic. Moreover, SAM technology can work remotely with smart technologies, which has been useful to monitor and prevent the spread of the pandemic. SAM technology has been ensuring that antibacterial bio-cellulose masks and ventilators, among other equipment, reach patients, preparing us better for viral outbreaks in the future [80]. SAM technology is a digital process. Not only can each product be represented by a digital file, but it can also be reproduced by anyone with a similar printer and the appropriate material, regardless of their location. On the other hand, SAM's digital nature creates new opportunities for innovation. By analyzing a product's lifecycle in a SAM environment, Fletcher [81] distinguishes five stages in DVCs:

- (a) Stage 1—Idea and design: It marks the beginning of the digital wire. As mentioned earlier, SAM technology can support design geometries and features that could not be achieved using subtractive techniques. The design phase supports the product from its conception, production, and distribution until the end of its useful life or it is decommissioned.
- (b) Stage 2—Speed to market: After designing the product, it proceeds to production, which involves the identification of materials and processes required. At this stage, issues of rapid prototyping, the use of new or smart materials, and new processes (including their integration across processes and technologies) and production close to the market are particularly important. Within this context, new possibilities and new opportunities arise. As already mentioned, SAM allows the use of smart materials and production close to the market.
- (c) Stage 3—Optimized production: optimization through “Digital Twin” (DT) reduces the complexity surrounding production and assembly in manufacturing as it allows



the simulation, monitoring and control of the process, as well as the reduction of material waste, machine operator time and printer depreciation. This virtual representation can help to understand the functions of various manufacturing parameters and the sensitivity of product quality to those parameters. The implementation of DT technology in smart additive manufacturing systems has shown great potential in enabling advanced manufacturing data management, developing simulation and prediction models, reducing development times and costs, and improving product quality and production efficiency [82,83].

- (d) Stage 4—On-demand supply: On-demand supply corresponds to a new stage in the DVC: the digital inventory. Since manufacturers can produce a physical product on demand from a digital inventory, they have greater supply chain security and significantly reduced costs. Commonly associated with production flexibility, SAM allows the production directly from digital files, available in digital inventories, without the need for tools or molds, enabling on-demand production and allowing SCs to quickly deal with demand fluctuations [84].
- (e) Stage 5—Controlled phase-out: The controlled phase-out eliminates the costs associated with storage and inventory, replacing the latter with a digital inventory of digital spare parts to be printed on demand. As mentioned in the previous point, by allowing production on demand, using digital files and digital inventories, SAM will avoid unnecessary storage and inventory costs [85].

Fletcher's [81] five stages in DVCs corroborate the ideas that have been presented above on SAM. Moreover, SAM impacts all Fletcher's five stages in DVCs. In addition, SAM can bring strategic and operational benefits in DSCs and corresponding DVCs, by highlighting the interaction with each agent, generate changes and organizational transformations, bringing an evolution in the way some products are produced, stored, and distributed. Specifically, SAM can bring competitive gains for companies that seek to reduce their waste in materials and transportation costs and accelerate a customized production response to increasingly demanding customers.

## 5. Conclusions

The impact of Industry 4.0 on entrepreneurship, innovation, economies, and societies has been a catalyst for strategic change as companies strive to remain competitive in their industries. The digital society and its technologies allow the fusion of the digital and physical worlds and create CPSs that revolutionize manufacturing practices and give rise to DVCs, which have generated unfathomable economic value for a decade. In this article, we critically review the literature and reflect on SAM impacts on production logistics, inventory management, and DVCs.

Digital transformation is affecting business models from resource acquisition to end user delivery, changing the way manufacturers think about the entire lifecycle of a product, from design, production, and distribution to the end of a product's life. SAM, combined with other new digital technologies, is redesigning every link in the supply chain, automating, and optimizing entire workflows, with a significant impact on manufacturing and business competitiveness. Throughout the process, companies, including SMEs, face financial, cultural, legal, technical and implementation difficulties, which must be overcome through the adoption of appropriate digital transformation strategies, combined with a culture of innovation in the assessment and planning of the inherent challenges and risks and some public support.

Smart manufacturing has been considered a successful improvement introduced by Industry 4.0, increasing resource efficiency and adaptability. It is a new generation of production systems comprising machines connected to the Internet to monitor the production process and improve its performance. It includes not only automation but also human-machine collaboration to improve operational efficiency. The wide application of the Internet and innovative engineering technologies has helped to integrate customer and business value processes and create a better manufacturing environment. Smart

manufacturing has contributed to the emergence of new technologies and manufacturing processes, new materials, data collection and analysis that shape future developments and applications as well as predictive models, sustainability, and enterprise resource sharing and networking.

AM technology plays a crucial role in this digital transformation, changing the way manufacturers think about the entire lifecycle of a product, from design, production, and distribution to the end of a product's life. AM has the potential to revolutionize strategically important sectors of the manufacturing industry. It can bring a reduction in supply chain complexity, flexible logistics and inventory management, customization of mass production, manufacturing decentralization, unprecedented flexibility in product design, rapid prototyping, production and delivery, resource efficiency and sustainability. Since 2020, it has played a key role in fighting the spread of COVID-19, providing custom parts locally on demand, reducing waste and shipping costs, and eliminating the need for an extensive manufacturing pipeline in the production of face shields, and palliative face masks. However, AM technology also poses regulatory, safety, and product integrity challenges.

AM technology is therefore a vital component of smart manufacturing. SAM can be defined as a fully integrated intelligent factory collaborative AM. SAM technology supports the integration of AM technology into smart factories, streamlining communication between devices and employing solutions to solve critical problems, in addition to enabling the application of smart materials and processes. It plays a crucial role in increasing the production efficiency of smart factories. Its impacts are not just limited to production in the factories, but also to other parts of the DSCs and corresponding DVCs, including logistics, inventory management and transportation. SAM technology reduces the complexity of DSCs and contributes to a more flexible approach to logistics and inventory management. It has been encouraging the growth and popularization of customized mass production as well as decentralized manufacturing. In addition, rapid prototyping has inspired greater design freedom, which among other factors, has led to better resource efficiency and sustainability. SAM technology impacts all Fletcher's five stages in DVCs: Idea and design; Speed to market; Optimized production; On-demand supply; and Controlled phase-out. However, the need for clear definitions and regulations on 3D printing of digital files and their reproduction, as well as health and safety issues that result from unmonitored production, cannot be ignored. Furthermore, investment in this technology is expensive and still prohibitive for many companies.

Finally, SAM technology can bring competitive gains for companies that seek to reduce their waste in materials and transportation costs, simplifying their processes, and accelerating a customized production response to increasingly demanding customers. SAM technology represents an excellent example of how digital technologies have matured, becoming an integral part of Industry 4.0 manufacturing revolution and with great influence on the locus of innovation and production.

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