Additive manufacturing in the supply chain

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Abstract

Additive Manufacturing (AM) is replacing traditional manufacturing approaches—such as subtractive and molding—in some industries. The product and supply chain impacts of AM continue to extend its industrial reach, improve engineer-to-order manufacturing, and pave the way to mass customization. This study explores the supply chain changes that may arise from a full or partial transition to AM-based production. Supply chain factors and dimensions that are greatly impacted are initially identified. Management and operational issues pertinent to each factor are discussed next, followed by a review of the current literature and the future of AM-based supply chains. The interrelationships between these factors are then investigated considering the disruptive impact of AM on supply chain management. Finally, the supply chain change matrix is presented for identifying the areas in that supply chains are expected to be impacted. This chapter is concluded by providing a summary of the findings and insights into AM-based supply chain transition.

Keywords: Additive manufacturing, 3D printing, supply chain management, SCOR, decision analysis

1. Introduction

The concept of disruptive technologies refers to a new technology that triggers serious changes in a system's routines and state (Bower and Christensen 1995). A disruptive technology discourages users from continuing with conventional methods. Disruptive technology remains a central idea both in academia and practice as well as in various contexts, only a few have resulted in revolution-like changes. The Internet is a prime example of a truly disruptive technology that altered business operations in many ways. Additive manufacturing (AM) is a more recent example of a disruptive technology, which is likely to revolutionize the production sector and its supply chain.

AM-based production is different from the traditional, subtractive approaches where raw material is carved or cut followed by complementary steps such as forging, grinding, drilling, and assembly to

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finalize a product (Ying et al. 2022). AM consists of a layer-by-layer addition of compound material for producing the physical counterpart of a digital product. In addition to its implications for product design, performance, and technical features, AM has a disruptive impact on the supply chain processes, stopping them from continuing with the routines that are designed for accommodating traditional production methods. Different logistical supports may be required for operating with AM-based production.

AM requires further development from the supply chain and operations management viewpoints to facilitate a wider industrial reach. Recent studies developed conceptual frameworks or discussed the implications of AM adoption on supply chain and logistics using literature reviews and interviews (Rogers et al. 2016; Braziotis et al. 2019; Silva et al. 2020; Sonar et al. 2022). The relationship between various aspects of supply chain changes has not been investigated; such investigation helps understand the underpinning of AM adoption, which determines its suitability in various sectors and supply chains. This chapter uses a systematic approach to explore the mutual influence between major change factors. The chapter introduces a supply chain change matrix for suggesting the best course of managerial actions and facilitating well-informed AM adoption decisions. Outstanding research is summarized to suggest potential directions for future developments in the field.

The supply chain operations reference (SCOR) is used as a framework for discussing the related activities considering the logistical elements of supply chains—facility, transportation, inventory, as well as sourcing (Chopra and Meindl 2015). The chapter also considers effective time horizons and the level of managerial influence at strategic, tactical, and operational levels (Gunasekaran et al. 2004). The plan, source, make-assemble, and deliver-return processes and their relationships to AM are separately discussed in the initial sections. Supply chain factors that are impacted the most by the disruptive nature of AM are identified in these introductory sections. The chapter is continued with a systematic analysis of the interrelationships between the identified factors and presents the supply chain change matrix. Finally, outstanding research and future directions are provided to contribute to this emerging supply chain topic.

2. Plan

The first step of the supply chain process deals with demand and supply planning as well as balancing resources to match market requirements. Outcomes of this stage regulate business rules to improve supply chain performance while making sure that the external regulatory and internal financial plans are fulfilled (Supply Chain Council, 2004).

The major planning decisions pertinent to the ***facility*** element of supply chain management include: (1) how many supply chain echelons are required from the acquisition of raw material until delivering the product to the final consumer—network configuration; (2) where to locate facilities and allocation of market and supply points to each facility; (3) how much capacity should be made available in each plant and how flexible each facility should be; and (4) how to organize the departments inside each facility and across the supply chain network. These decisions are rather strategic with a medium- to long-term planning and decision time.

In an AM-enabled supply chain, the parts-products can be often produced in-house or outsourced to a single third-party service bureau—supply tiers will be shorter. Fewer machines are usually involved in the production of parts-products using AM; there is relatively less need for assembly with less space required. Companies will be able to make production capacity more distributed. With an increase in the availability of 3D printers due to technological development and reduced cost, the facilities can be located closer to the point of consumption. This situation will result in inbound logistics of raw materials that can benefit from economies of scale due to the limited variety of raw materials. Outbound logistics will offer a reduced response time to market demand at a reasonable cost.

Considering that AM machinery is generally more flexible than traditional manufacturing machinery, production plants can operate at a lower capacity given that fewer single-purpose machinery will be required. Departmental layouts within and across facilities will require more careful design operations in AM-based production when compared to traditional approaches. AM operations will require lessened material handling and less operator involvement. Alternatively, AM-based production tends to be cleaner than subtractive methods; this may help reduce the distance and barrier between production and other departments, which can improve information flow and multidisciplinary communications. Less required shop floor space and manpower, with streamlined supply processes, results in potential merger of production and distribution facilities in AM-based supply chains leading to reduced operational costs and time, with operational effectiveness improvements.

The second logistical element of supply chain management, ***inventory*** planning requires decisions at both strategic and tactical levels—which means short- to mid-term time horizon considerations. The most prominent inventory planning decisions include (1) the type and amount of inventory to hold; (2) the location of inventory across the supply chain; (3) inventory replenishment processes; and (4) determining the state of the inventory items (i.e., quality) and dealing with excess inventory.

AM can radically change the nature of inventory planning in supply chains. *First*, the type of inventory will gradually alter in the production sector. Companies may not require part and component inventories, instead, raw materials would be stored near 3D printing operations. The inventory portfolio will be less diverse and easier to manage in this situation. For example, quality control may be cheaper due to the limited variety of materials.

Second, time in the supply chain will decrease. A shortened value chain means time will become less critical for maintaining response levels. Assuming that replenishment will go as planned—that is, on-time delivery and no disruptions—the company can place new replenishment orders at shorter intervals. Inventory turnover and usage will improve. This result means the cash flow will also improve, and the company will be less impacted by the market turbulence. From a risk perspective, the stored inventory will generally be of less monetary value (little or no value-added) and the costs of unforeseen events will be less.

This shift in inventory means it can be kept closer to the point of sale or consumption time. Given that the transformation of material to final products can be postponed and the same material can be used for a wider range of products, the chances of having excess inventory will decrease. The supply chain will be less burdened by inventory depth and width. The supply chain can operate more efficiently. Operational wastes and non-value-adding activities can be minimized.

Third, from the planning perspective, the possible changes in inventory of AM-based supply chains reduce the need for accurate forecasts. It will also be less likely to face stockout situations due to the use of standard or common raw materials and the possibility of fulfilling new orders in shorter times.

The third logistical element, ***transportation*** is responsible for moving raw materials, support tools, parts and components, and final products between facilities in a manufacturing supply chain. Planning of the transportation activities consists of determining the following major tactical and operational decisions: (1) What mode(s) of transportation to employ; (2) How much capacity to use and how to allocate the available capacity (load planning); and (3) How to plan the operations (routing and scheduling).

The selection of transportation mode is mostly impacted by the volume and weight of the shipping material, their monetary value, logistical requirements, the distance between the origin and destination, and geographical characteristics. Postponing final production closer to the point of consumption means the transportation volume per unit of product is smaller in an AM-based supply chain. This characteristic is particularly important because of having raw material as the dominant material flow and less packaging is required compared to traditional systems where the parts and components must be shipped with additional care.

Overall, fewer shipments between facilities may be required in an AM-based supply chain and the inbound logistics to the production facilities will be long-haul and mostly for transporting raw material. Fewer material movements occur inside a production facility because of the streamlined value chain and by the fact that items can be produced in fewer steps. Given that the raw and unprocessed material has a lower monetary value per unit of weight, the need for long-haul transportation justifies the use of cheaper modes of transportation, such as maritime and railway shipping. In this setting, the use of third-party logistics service providers may become more prevalent. Considering that the frequency of shipment to each production facility can be reduced with full-truckload transportation of 3D printing material, the routing decisions become less relevant for inbound logistics. The reduced variety of shipping items in inbound logistics reduces the complexity of capacity allocation decisions and demand divisibility.

In general, AM can reduce supply chain *planning* complexities. Streamlined supply stages can address some bullwhip effect concerns. Lessened material diversity and greater supply pooling have implications for supply planning and demand forecasting in make-to-stock systems. AM can also facilitate a shift to make-to-order agendas in certain industries. The product and supply chain impacts of AM together alter the pricing element of supply chain management, especially for mass customization. In addition to improving the company's profitability, a customer that can benefit from highly customized products is more likely to tolerate revenue management practices, like different delivery-time fares and pricing concerning service levels.

3. Source

The *sourcing* step of supply chain management consists of managing *infrastructure*, equipment and *tools*, procuring *raw materials*, and *managing suppliers* (Supply Chain Council, 2004).

AM-based production facilities in a supply chain can be equipped with a relatively smaller variety of machinery when compared to traditional manufacturing. This is because 3D printers are highly flexible and can produce a wider variety of parts or products with minimum setups compared to multi-purpose subtractive machines. There is relatively less need for assembly operations, which reduces the need for extra operational space. Less need for tooling operations has also become possible with the recent development of hybrid AM technologies that complete the post-processing tasks on the same machinery.

A company that upgrades its current facilities with advanced 3D printers may save room for increasing the production capacity, repurposing freed space, or downsizing production sites. When designing new supply chain networks and facilities, the need for smaller production spaces enables organizations to invest in constructing a more distributed manufacturing network to better benefit from the supply chain impact of AM.

AM-based operations are generally more sustainable than traditional manufacturing due to significantly less production waste and externalities. In the context of infrastructure management, generating less noise and pollutants enables the decision-makers to locate the AM machines in the same facility as the engineering design and administrative offices. These aspects together make it easier to manage infrastructure in an AM-enabled supply chain.

One of the main advantages of AM over traditional manufacturing is the ease of using composite materials, which helps improve product characteristics and performance. Although the use of composite materials may extend the supply chains vertically, it simplifies the procurement procedure for the original equipment manufacturers, allowing them to contract out the responsibility of dealing with low-tier suppliers to the main supplier.

AM machines can produce complex geometries in a single production run with less need for keeping work-in-progress components and purchased sub-component inventories. Inbound inventory to the AM-based production facilities is limited to a handful of materials. The variety of feedstock materials in the market used to be a major barrier to the wide adoption of AM technology, but the range of materials is extending quickly.

Currently, different types of metals, graphite, carbon fiber, and plastics can be selected as feedstock for AM machines. The production of modular products is another relevant advantage of AM that reduces the sourcing complexities in the supply chain of certain industries, like consumer electronics and mobile phones. Finally, the growing market of digital material on the open-access and paid platforms are expected to have a sharp impact on the sourcing element of the supply chain; the final product manufacturer may choose to purchase the digital product and produce the required components in-house. This situation reduces the product cost and sourcing complexities in the manufacturing supply chains and alters the demand chain, particularly in the downstream supply chain.

Overall, the sourcing process in supply chain management comprises answering the following tactical and operational questions: (1) What technology is suitable for producing the parts/products; (2) Can the parts be produced in-house, or the AM-based production procedure should be outsourced; and (3) How to select the best third-party printing service provider.

AM technology selection decisions should be made considering design requirements and desired printing material. This decision, in turn, impacts infrastructure requirements, operational costs such as energy consumption costs, and investment costs. Generally, 3D printing technologies can be categorized considering the production process—additive, solidifying, or lamination—and the base in which the items are produced such as liquid, solid, or powder. Vat photopolymerization uses light-activated polymerization in the production process, which requires a low energy level, placing this technology at the bottom of the energy list of the major AM processes; it is followed by material jetting, binder jetting, material extrusion, sheet lamination, powder bed fusion. The AM processes based on directed energy deposition require thermal energy for melting the feed, which makes it the most energy-intensive AM technology (ISO/ASTM 52900 2021).

The compartment size of the AM machines has been reduced significantly over the years and the overall size of the machinery is mainly determined by the build size on which the products are processed. The learning curve for AM machines may vary, therefore it is important to ensure that the purchased machinery follows certain standards, both in software and hardware. Extrusion-based AM machines are comparatively cheaper than the other alternatives and various plastics can be used as feedstock (filament) for extrusion-based AM machines. Desktop 3D printers are widely used for private and home purposes while industrial extrusion-based machines have recently been employed for mass production of parts and final products.

Powder bed fusion-based AM is on the other edge of the AM technologies concerning the cost of machinery and equipment. Considering that metals can be used as feedstock for powder bed fusion-based AM machinery, this AM technology is currently the main technology used at the 3D printing service bureaus and is expected to dominate the application areas that require material removal.

Production complexity, the required endurance, quality (i.e., surface roughness and dimensional accuracy), and the size of the part/product are fundamental considerations in determining whether to use AM-based production methods. These factors may also vary from one 3D printing service provider to another due to the use of different brands and types of AM machinery. Overall, the selection of the 3D printing service provider requires the following considerations: the unit production cost, cost of raw material, service time, the range of material/color/size and AM technology choices, production capacity, and post-processing services.

The location of the AM service provider is important to take full advantage of the supply chain impact—that is, considering the ease of logistics of the final product. Finally, AM may have implications for supplier development; AM platforms facilitate the direct involvement of the supplier in the design and generation of the digital models and make it also easier to monitor and improve the supplier's performance. Besides, a smaller supply base forms strategic partnerships where the company can invest more in supplier development programs.

4. Make or Assemble

The *make* element of supply chain management is responsible for transforming raw materials and parts from the *source* activities into complete products for *distribution* to the final consumers. It consists of product development and launch, managing the production process, and activities like assembling testing, and packaging (Supply Chain Council, 2004). The major impacts of AM on the *make* activities include (1) the supply chain's pull/push strategy and the respective decoupling point; (2) the scope and nature of the operations; and (3) quality management.

In an ideal operational situation, the products are made in direct response to customer demand with no inventories being kept along the supply chain (make-to-order). In most cases, companies are unlikely to be able to efficiently fulfill orders on time by applying a supply chain-wide make-to-order policy. Manufacturing supply chains hold inventories to cope with demand fluctuations and benefit from the cost advantages of scale economies, the so-called make-to-stock approach, and push strategy. The decoupling point determines the boundary between 'pull' and 'push' operations in a supply chain.

In an AM-based supply chain, the possibility of having a highly distributed manufacturing network—closer proximity of the production facilities to the final customer—together with a streamlined value chain reduces the response time. This situation enables the companies to pursue just-in-time production and move the decoupling point closer to the ideal make-to-order approach. Additionally, a flat cost curve in AM makes the economy of scale in production less important when compared to traditional manufacturing. The mentioned advantages of AM may shift the supply chain of certain products away from make-to-stock. AM facilitates responsiveness and differentiation strategic agendas but may not result in cost-effectiveness in its current state of development.

From a product development and launch perspective, AM can facilitate a shorter time-to-market. This is mostly due to AM prototyping capabilities; the fact that the design procedure becomes faster and cheaper, and the improved connection between the design and production stages. With AM streamlining the supply chain process, the emphasis on soft operations and services, like design and marketing will become more prevalent. In this situation, the make-to-order concept can be enhanced to engineer-to-order; that is, the design and engineering of the product will constitute a more significant proportion of the value chain in industries with a high degree of customization.

With a shift in supply chain capabilities, the operational scope can also be extended beyond the point of consumption; that is, integrating demand chain management into the supply chain. Big data analysis is currently employed for informing marketing activities, but little has been done to enhance the product design capabilities supported by big data analysis of unstructured data sources like social media. This will be particularly helpful for improving the design activities.

Disruptive new technologies—like blockchain and virtual reality—can be employed as enablers for a paradigm shift in supply chains. In these cases, products and services can be extended and may require business model adjustment. Many businesses may have to shift to providing digital products and services in addition to or instead of physical products. In this situation, the 'make' process of the supply chain may experience a significant change. For example, if a product can be made using desktop 3D printers at home, the consumers may opt to purchase the digital document instead of the physical final product. Alternatively, they may prefer to take the digital document to a local 3D printing service bureau to have the final product in a shorter time and at a cheaper price. Either way, virtual reality can assist in facilitating the design process and improve the designer-customer interactions. As another example, the copyright and intellectual property-related issues of digital products can be addressed using blockchain technology.

The AM production process is different from traditional manufacturing approaches where the raw material is carved or removed, and additional steps like forging, grinding, drilling, and assembly must follow to prepare the final product. In contrast, AM constitutes a single production run with few post-processing requirements. The material cost, process type, and the extent of post-processing requirements determine the production costs.

Overall, the unit production cost with AM is cheaper than traditional approaches for low- to mid-volume production considering the flat cost curve. For high-volume production, however, the unit production cost is higher than traditional approaches in the current state of developments in AM. Despite the high investment cost and the unit cost for high-volume production, high flexibility in producing complex geometries, high surface roughness, and feature resolution with a fine level of detail makes the AM a better alternative for producing certain products.

Technological development, demand growth, and a competitive market with more producers are expected to help lower the prices of AM machinery and feeding materials in the coming years. Besides, improved know-how of the operations management aspects will reduce the operational costs and facilitate the industrial reach of the 3D printing machines.

Testing the quality of raw material, work-in-progress, and the final product constitutes another major aspect of the 'make' activities in a supply chain. The streamlined value chain in AM-based supply chains reduces the testing and packaging needs. Although a highly distributed production network in AM-based supply chains may not benefit from economies of scale in quality control and delicate testing approaches, higher precision and flexibility of AM machinery compared to the traditional manufacturing approaches improves product quality.

AM can be used as an enabler for improving production performance—for example, by making tools, jigs, fixtures, or casts to be employed in certain operations. Similarly, a timely supply of parts or components for the repair and maintenance activities helps shorten the possible downtime and reduce the chance of machine breakdowns.

AM mockups and other assistance tools can come in handy for improving operator performance, when required, in the training programs. These support capabilities, in turn, improve the supply chain performance, for example, by avoiding delays caused by tooling shortages and decreasing reliance on tooling suppliers and maintenance service providers. Finally, and from a value chain perspective, using AM for the in-house production of parts and components enables the company to have better control over the quality variables and continuous improvement initiatives.

5. Deliver and Return

The *deliver* activities in a supply chain include order management and the routine warehousing and distribution operations for fulfilling the orders. *Return* activities consist of handling the returned items, like containers, packages, defective items, and end-of-life products (Supply Chain Council, 2004).

AM adoption can radically change make-to-order and engineer-to-order supply chains. Receiving orders, making decisions on acceptance, rejection or backlog, and signaling the production department to initiate the 'make' activities will all be impacted. Depending on the type of the product, the customer may customize the purchase at a retail store or a local service provider (e.g., footwear), or use the online platforms for selecting the design and configuration of the product (e.g., consumer electronics).

Metaverse—virtual reality—platforms can reduce shop visits for product customization with the help of interactive tools and new technologies, like virtual reality and holograms. While rejecting an order in traditional supply chains is often caused by raw material or production resource shortages, design and compatibility aspects may be the new considerations for order management decisions in mass customization businesses. Although the adoption of AM-based production may not significantly impact order management for make-to-stock production, the increased flexibility in both production volume and variety can facilitate order fulfillment in uncertain times. This flexibility potentially reduces the time between receiving an order, starting the production procedure, and delivering the final product.

Finally, using AM as a backup production capacity along with the subtractive machines, or vice versa, can help the traditional supply chains deal with demand fluctuations more effectively. This situation has implications for order management in both make-to-order and make-to-stock supply chains.

From the transportation management perspective, the frequency and type of last-mile services impact order fulfillment operations. The question is, should the final products be sent directly from the production plant or the central warehouse for door-to-door service, or should customers pick up the item either from designated locations (like convenience stores) or the retail stores that may be comparatively further away. Either way, organizations should determine how much inventory of raw material and finished goods should be made available in each warehouse and retail facility to avoid lost sales and backlogs while keeping the overheads at an acceptable norm.

How these decisions are impacted by a shift to AM-based production is mostly about the differences AM makes in operational responsiveness or cost-effectiveness. Considering the distributed nature of AM and the proximity of production facilities to the final consumers, distribution operations are mostly business-to-consumer (B2C). B2C requires vehicle routing decisions to plan and optimize doorstep deliveries. The other significant supply chain impact of AM is the supply of products to remote areas and places with harsh climate conditions. The possibility of producing the items in remote places instead of having them regularly supplied from globally scattered suppliers helps the development of such areas, which is in line with sustainable development goals. This situation also reduces operational costs, distribution-related externalities, and supply chain resilience.

In addition to the cost of capital for holding inventories, warehousing costs are associated with the storage and management overheads as well as running expenses; this cost category is regarded as one of the main sources of supply chain expenses. In an AM-enabled supply chain, the cost of capital for inventories is relatively low because inventories are most often unprocessed with little value-added. Additionally, the running costs are lower than a traditional supply chain considering that the depth and width of inventories are comparatively limited. These inventories often occupy less space, and the final products are lightweight when required. For the same reasons, consolidation of raw materials can lower the inbound transportation costs.

AM-based production is more distributed likely making last-mile delivery cheaper. In addition to the financial aspects, the market coverage, and the control of the company over the logistics operations impact warehousing decisions. Overall, a cost-effective supply chain can benefit from AM adoption by lowering operational costs while responsive supply chains may use the saved overheads for improving service levels or extending the service range.

Product conformity and quality are expected to improve in AM-based supply chains. With fewer returned and defective items, the operational burden over the logistics capacities can be alleviated. Using less packaging along the supply chain will reduce the problem of dealing with the packaging material. End-of-life products and recycling operations means the processes of dismantling, separating, and recovery of components can be significantly changed by AM. The type and uniformity of raw material used in AM production and the fact that fewer joints and connections are used for attaching parts are some of the major factors impacting recycling operations. The product impacts of AM and the flexibility it provides may facilitate the design for disassembly, recovery, and reuse and improve the closed-loop operations. In this situation, the supply of the feedstocks may be facilitated through the 'return' of used and end-of-life products in AM-based supply chains.

As a relatively new design concept with implications for logistics, it is expected that the Do-It-Yourself model will be advanced to a new level by AM. This change will occur in industries where the distribution of physical products can be replaced by the sale of digital products, which can be produced at consumer location.

As an alternative solution, new businesses, like local 3D printing service bureaus and hubs should be established to provide production and design services that reduce the distribution expense and time and improves customer customization experience. AM can support disaster response and emergency use cases, where regular supply chains are impacted or cannot promptly supply the basic needs and medical requirements. Production of necessities, like ventilator and oxygen valves, face shields, swabs, and 3D printed lung models in the early phases of the COVID pandemic (Arora et al. 2020), and customized implants for surgery in emergency rooms are prime examples of the medical applications of AM.

6. Supply chain change matrix

A systematic approach called the decision-making trial and evaluation laboratory (DEMATEL; Fontela and Gabus 1976), can be used for developing the supply chain change matrix. DEMATEL explores the decisive factors in a system to help understand its underpinnings (Falatoonitoosi et al. 2013). It is worthwhile noting that DEMATEL does not determine the importance of the factors; instead, it analyzes the interrelationships between them to find the most influential factors and the cause-effect relations. In this definition, a factor may be considered the least important factor in terms of importance weight (which is determined using multi-criteria decision-making methods like AHP, ANP, etc.), but shows the highest influence on the rest of the factors.

Expert opinion is the basis for analyzing the interrelationships between the supply chain change factors. This kind of analysis is particularly important when a new phenomenon, i.e., a disruptive technology is being studied and there is not enough evidence to generate meaningful information. In a nutshell, the analysis defines the prominence and role of different supply chain changes caused by the adoption of AM-based production. A brief explanation of the computational steps is provided below, followed by a detailed analysis of the results, and summarizing some previously determined results in this chapter.

Step 1: Data collection. The supply chain change factors developed by experts are listed in Table 1. Expert opinion was gathered using the question: "When assessing the disruptive impact of additive manufacturing on the supply chain, to what extent does the factor in the row influence the factor in the column?”. The answers are selected from “No Influence”, “Low Influence”, “Moderate Influence”, “High Influence”, and “Very high influence”, and are entered into every cell of the relationship matrix. The resulting matrix is called the direct-relation matrix. Simple averaging is used for aggregating opinions.

Step 2: The supply chain change matrix preparation. The computations begin with normalizing the direct-relation Matrix. Every element of the direct-relation matrix is divided by the greatest summed value amongst all rows and columns. The resulting normalized matrix is then multiplied by the reverse of its difference from the identity matrix. The resulting matrix represents a convergence of the cell values after infinite rounds of multiplications.

Step 3: Prominence and net-causation analysis. The change factors should be categorized into cause or effect classes to analyze the supply chain change matrix. The summation of matrix rows shows the total influence of a factor on the rest of the factors. The summation of the column values of the matrix shows the total influence received by each factor. On this basis, the prominence value refers to the total influence dispatched and received by a factor; greater prominence values show that the factor contributes greatly to the supply chain changes in the AM adoption process. The net causation determines the difference between the dispatched and received values. Change factors with a positive net-causation value are the major influencers and those with a negative value are significantly influenced by the rest of the change factors. It is apparent that the influencers should be given higher attention to ensure better outcomes in the supply chain transition process.

Table 1. Supply chain change factors.

Dimension	Symbol	Factor	Explanations
Strategic	**F_1**	Network configuration and facility location	How many supply chain echelons are required from the acquisition of raw material until delivering the final product to the ultimate consumer? Where to locate the production facilities and how to allocate market and supply points.
	F_2	Outsourcing and service provider selection	Can the parts be produced in-house, or the AM-based production procedure should be outsourced; if so, what criteria to consider for selecting the best third-party 3D printing service provider?
	F_3	Supply chain strategy	Where to place the decoupling point considering the push-pull view of the supply chain. What is the targeted competitive advantage; cost-effectiveness, responsiveness, and/or differentiation?
	F_4	Scope of operations	Modifying the scope of the supply chain activities (or the business model) when required. Adding new services and products, using new technologies for extending the customer experience, or revising outsourcing decisions.

	F5	Closing the supply chain loop	How the AM adoption benefits the five Rs (i.e., Reduce, Reuse, Repair, Rot, and Recycle) for reducing waste and managing the take-back initiatives.
Tactical and operational	**F6**	Production capacity	How much 3D printing capacity should be made available at each plant? how flexible each facility should be? Is there a need for keeping some subtractive production capacity?
	F7	Production technology and material selection	What materials are required in the production of parts/products? What technology is suitable for producing them? What are the post-processing requirements?
	F8	Operation schedules	When to produce the product and how to schedule the deliveries? How to coordinate the parties involved in the value chain.
	F9	Inventory level, replenishment, and location	What type and amount of inventory to hold and where to keep these inventories across the supply chain? When to initiate the inventory replenishment procedure considering the lead time and availability of the supply sources.
	F10	Quality control	How to check the state of the inventory items, including raw materials, the quality of services, and/or products. How to implement the process control measures.
	F11	Transportation mode and capacity	What mode(s) of transportation to employ considering the type and size of the final products? How to allocate the available logistical resources?

Expert opinion inputs are presented in Tables 2-3. The computational procedure explained above is applied for the analysis of the results.

Table 2. Input from one expert.

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**
F1	-	H	H	L	L	VL	VL	H	L	H	H
F2	VL	-	VL	H	L	VH	VH	L	L	VH	L
F3	VH	H	-	H	L	H	H	H	H	VH	H
F4	L	VH	L	-	H	VH	L	H	L	L	H
F5	L	H	H	VH	-	L	H	VL	L	L	H
F6	L	H	L	VH	H	-	H	H	H	L	VL
F7	L	VH	VL	H	L	H	-	H	H	L	L
F8	N	L	L	H	H	H	L	-	H	L	L
F9	VL	VL	VL	L	L	H	H	H	-	L	H
F10	L	H	H	L	VL	VL	H	H	L	-	VL
F11	L	H	VL	L	L	L	VL	H	H	L	-

Table 3. Input from another expert.

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}
F_1	N	H	VH	H	H	H	L	L	H	H	H
F_2	H	N	H	H	H	H	H	L	H	L	L
F_3	VH	VH	N	VH	H	H	VH	H	H	L	H
F_4	H	H	H	N	L	L	L	L	L	L	H
F_5	H	H	VH	H	N	H	H	L	H	H	H
F_6	H	H	L	H	L	N	L	L	H	L	H
F_7	H	H	H	H	H	L	N	L	L	H	L
F_8	L	L	L	L	L	H	L	N	H	L	H
F_9	H	H	L	H	L	L	L	L	N	L	H
F_{10}	H	L	L	L	H	L	H	H	H	N	L
F_{11}	H	L	L	H	L	L	L	H	H	L	N

Table 2 presents the supply chain change matrix resulting from the DEMATEL analysis; darker cells highlight higher total relationship values. On this basis, 'supply chain strategy' has the greatest influence with its interrelationship with 'outsourcing and service provider selection' being the most significant in the matrix followed by that on the 'scope of operations'. The supply chains that emphasize different strategies may take advantage of the AM adoption in different ways. For example, it might be more effective to implement a partial adoption of AM in a certain stage of the supply chain and a certain industry. Moreover, the company strategy determines whether the product impact of the AM is required the most or the company should focus on the supply chain impact of the AM adoption. The supply chain phases that experience the heaviest load or the bottleneck may require a boost through the AM adoption.

Considering that tactical and operational factors received the greatest average influence in the change matrix, one can suggest that a great deal of change in supply chain activities from tactical and operational levels is mostly triggered by the changes the AM adoption imposes through the strategic elements.

A partial supply chain transition to AM may not require structural changes in the strategic elements of the supply chains; therefore, a hybrid of subtractive and additive methods may be the best solution for many sectors. Overall, the extent and pace of adoption vary across industries. It is worthwhile noting that the greatest self-influence in the factor 'outsourcing and service provider selection' suggests that any changes in this factor may result in sequential changes in the outsourcing activities due to identifying new operational needs and market opportunities.

Table 4. The supply chain change matrix.

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}
F_1	0,2698	0,4022	0,3578	0,3888	0,3374	0,3467	0,3271	0,3532	0,3682	0,3562	0,3667
F_2	0,3263	0,3159	0,3154	0,4011	0,3363	0,3852	0,3790	0,3374	0,3657	0,3535	0,3365
F_3	0,4363	0,4814	0,3118	0,4804	0,3926	0,4328	0,4367	0,4238	0,4417	0,4115	0,4240
F_4	0,3356	0,4096	0,3252	0,3109	0,3326	0,3687	0,3342	0,3466	0,3489	0,3234	0,3605
F_5	0,3592	0,4228	0,3727	0,4349	0,2808	0,3773	0,3836	0,3424	0,3846	0,3584	0,3831
F_6	0,3340	0,3953	0,3111	0,4085	0,3317	0,2820	0,3463	0,3452	0,3736	0,3219	0,3334
F_7	0,3341	0,4087	0,3114	0,3952	0,3318	0,3544	0,2748	0,3454	0,3605	0,3361	0,3326
F_8	0,2639	0,3326	0,2808	0,3471	0,3018	0,3354	0,3021	0,2423	0,3420	0,2908	0,3153
F_9	0,2894	0,3315	0,2668	0,3449	0,2873	0,3201	0,3127	0,3141	0,2548	0,2902	0,3275
F_{10}	0,3107	0,3539	0,3022	0,3402	0,2950	0,3018	0,3360	0,3350	0,3350	0,2403	0,2947
F_{11}	0,3016	0,3435	0,2670	0,3440	0,2870	0,3069	0,2857	0,3269	0,3402	0,2903	0,2420

The prominence and cause-effect analysis are provided in Table 3 to analyze the supply chain change matrix with an overall lens. 'Supply chain strategy' is regarded as the change factor with the highest prominence; this supply chain factor is the one AM adoption is expected to interact the most. 'Outsourcing and service provider selection' is regarded as the second most-prominent change factor; contracting 3D printing service providers can be the best starting point of AM adoption for the sectors that require more significant investments and for SMEs. As supply chains transition to AM, new activities may be added to the operations by either bringing back the outsourced activities in upstream to the focal company or adding new services and features to the downstream supply chain. This is confirmed by the fact that F2 and F4 received the most influence in the change matrix. The extent of changes in these factors may result in business model changes.

Table 5. Prominence and cause-effect analysis.

Factors	Dispatched	Received	Prominence	Net
F_1: Network configuration and facility location	3,8740	3,5609	7,4349	**0,3132**
F_2: Outsourcing and service provider selection	3,8525	**4,1973**	**8,0498**	-0,3448
F_3: Supply chain strategy	**4,6729**	3,4222	**8,0951**	**1,2507**
F_4: Scope of operations	3,7962	**4,1960**	7,9922	-0,3998
F_5: Closing the supply chain loop	4,0998	3,5142	7,6140	**0,5856**
F_6: Production capacity	3,7828	3,8114	7,5942	-0,0286
F_7: Production technology and material selection	3,7852	3,7181	7,5032	**0,0671**
F_8: Operation schedules	3,3540	3,7126	7,0666	-0,3586
F_9: Inventory level, replenishment, and location	3,3392	3,9152	7,2544	-0,5761
F_{10}: Quality control	3,4448	3,5726	7,0174	-0,1279
F_{11}: Transportation mode and capacity	3,3353	3,7162	7,0515	-0,3810

The supply chain strategy, network configuration, and closed-loop factors are the change factors with meaningfully positive net causation, meaning that these factors are the major influencers in the change matrix. Expectedly, 'supply chain strategy' has the greatest amount of influence while receiving marginal influence from other factors; this is because the company's strategy determines AM adoption it seeks. As a prime example, a cost-effective supply chain may target centralized AM to take advantage of economies of scale to bring down costs while a responsive supply chain requires a highly distributed production network of 3D printers. The extent of decentralization is also expected to be industry-specific and influenced by the market size. 'Inventory level, replenishment, and location' is associated with the greatest negative causation value, which suggests that a change in this operational factor after the AM adoption is highly dependent on the changes in other factors.

7. Outstanding Research and Future Directions

AM is in the early stages of development; a reduction in AM machinery price, a higher level of autonomy, and shorter production times as a result of technological advances will facilitate AM adoption and its industrial reach (Khajavi et al. 2014). The supply chain know-how of AM is also quite important; the possible impacts of such a transition should be examined from different supply chain operational, tactical, and strategic perspectives. This section reviews outstanding AM-based supply chain management research based on which, directions for future research are suggested.

AM adoption decisions. Despite the advantages of AM over traditional manufacturing approaches, AM adoption is not a one-size-fits-all solution. Many considerations should be examined when evaluating its suitability for a certain industry situation and use case. For example, demand size and feedstock material cost are recognized as influential factors (Scott and Harrison 2015). From an operational perspective, the limited variety of materials and lack of expertise are some of the major factors that should also be considered (Choudhary et al. 2021). Legal aspects of AM adoption, like supply chain information integration, intellectual property and counterfeiting issues (Chan et al. 2018) are other considerations, which may require the adoption of cyber-physical systems (Gupta et al. 2020) and smart contracts of blockchain. AM enables a customer-centric supply chain based on value co-creation sources (Martinelli and Christopher 2019); hedonic motivation and DIY mentality are key factors for AM acceptance (Halassi et al. 2019), which may or may not be in favor of its adoption for certain customer groups. Multi-criteria decision-making and analysis models as well as expert systems are required to assist the multifaceted AM adoption decisions.

Application areas, like apparel, automotive, spare parts, plastic reforming, medical and insole manufacturing industries, as well as humanitarian logistics have been projected as the best venues for AM adoption. With a deeper analysis of the product and supply chain impacts of AM and the help of complementary technologies, this list can be extended. A comprehensive study on major product categories and the possibility of matching the groups with the existing use cases of AM will help the rapid adoption of AM. Finally, comparative studies on AM adoption in various industries and situations are another missing item in the academic literature that can be considered as a future research direction.

AM adoption requirements and transition path. AM adoption is more complex than deploying 3D printers in a production facility; a supply-chain-wide transition is necessary to enable the shift. A change in this scale requires well-informed planning to ensure a smooth shift to AM-based production. Case studies in different sectors are needed to shed light on the prerequisites of AM adoption. Besides, AM implementation requires broad involvement from different supply chain partners (Luomaranta and Martinsuo 2019), proactive top management, effective strategy for collaboration and innovation, skilled workforce for technology adoption, and resource allocation for digitalization (Priyadarshini et al. 2022). The planning aspects during and after the transition should consider these and additional considerations; a promising direction that requires investigations in the academic literature.

The present chapter identified the most influential supply chain elements and those that will be impacted the most because of AM adoption. This impact may also vary on different supply chain players. Manufacturers with diverse bills-of-material and direct digital manufacturing techniques are expected to be the change hot spots in a transition to AM (Sasson and Johnson 2016); supply chain resilience should be studied considering the change hot spots during and after the transition. The need for local production of essential goods using AM machinery demands the availability of feedstock material and improvement in local design services (Corsini et al. 2022); these are the other related topics to investigate from a supply chain resilience perspective.

AM adoption settings. The optimum AM adoption setting varies for different situations. For example, in sectors with rather high customization, the retailer's profit will be maximized if the manufacturer leads the customization process (Sun et al. 2022). The degree of postponement, manufacturing technology, and production quantity are other case-specific variables (Ramón-Lumbierres et al. 2021). The same applies to supply chain network configuration. The best configuration for an AM-based supply chain may be the one that simultaneously benefits from centralized production and the flexibility of local manufacturing (Khajavi et al. 2018). Centralized supply chain networks may be desirable when the demand rate is high (Li et al. 2019). In other cases, a decentralized AM-based supply chain offers more flexibility and better service levels when the distances between supply chain entities are long and the average demand is high (Rinaldi et al. 2022).

Another topic to investigate is the extent of AM adoption in a supply chain. Partial adoption of AM, for example as a supplementary production capacity, improves supply chain lead time and total cost (Chiu and Lin 2016). AM machines can be purchased by any of the supply chain partners, but advantages may be significant when the manufacturer adopts AM technology (Arbabian 2022). Supply chains' main hubs can be equipped with AM and redundant production capacity can be considered in other facilities using traditional manufacturing means (Strong et al. 2018). It is also found that including an AM hub in the supply chains improves closed-loop operations concerning economic sustainability (Son et al. 2021).

System dynamics, game theory, simulation, and optimization models have been developed to study the configuration aspects of AM-based supply chains; most of these studies are generic and have not been tested in real situations and using real-world data, which should be the focus of future research.

Supply chain mapping and cost analysis. The next direction includes case studies in different sectors and regions for AM-based supply chain cost analysis, risk analysis, and mapping. In general, AM adoption brings about performance improvement at both firm and supply chain levels (Delic et al. 2019). AM adoption improves supply chain flexibility, which, in turn, reduces operational costs (Delic and Eyers 2020). AM also decreases raw materials inventory considerably (Kunovjanek and Reiner 2020). A significant cost reduction has been reported for small-scale supply chains of highly customized products, like the insole manufacturing industry (Cui et al. 2021). Such case-specific evidence is required in other industry situations to facilitate the shift to AM-based production. Besides, AM adoption for certain product characteristics may benefit the most from certain operational viewpoints; for example, in-site production of large and very large steel products is particularly attractive from a transportation perspective; this needs to be investigated through supply chain mapping and cost analysis.

Sustainable supply chain and AM. One effective way to promote the adoption of new technologies is to explore their implications for pursuing sustainable development goals. This is especially true when achieving certain targets is hard or infeasible with traditional technologies and methods. Sustainable supply chains and AM require more investigations to unfold the hidden opportunities of the new production technology. AM adoption increases production speed, competition over fashion cycles, and product price; these bring about positive social sustainability impacts (Hohn and Durach 2021). There also is a positive interaction between AM machinery availability and consumer attitudes to social sustainability (Beltagui et al. 2020). It is a good practice to include environmental considerations in all steps of the possible AM-based supply chain transition. AM-based businesses can be more profitable when emission efficiency and waste minimization technologies are adopted (Thomas and Mishra 2022). As another example, recovering 3D printing wastes has shown to be beneficial (Santander et al. 2020); such circular ways of supply chain operations require development in the academic literature.

Finally, the *human* aspect of AM-based production operations received recent attention; AM should be investigated from Industry 5.0 perspective, for example by testing creative workspaces and learning platforms with the use of extended reality.

8. Concluding remarks

Compared with the traditional manufacturing approaches, which use material removal and/or injection molding, AM can more effectively produce items with complex designs and compound materials. In addition to the product-related impacts, it is believed that both full and partial AM adoption decreases supply chain cost, improves quality, speed, and flexibility, and facilitates innovative business ideas. These benefits have made AM a new technology with disruptive impacts on the supply chain. This chapter explored the change factors considering the supply chain transition toward AM-based production.

The AM adoption disrupts, among other things, the way the supply chain elements interact. The influential interrelationships between the pairs of supply chain change factors under AM are, therefore, expected to be different than under traditional manufacturing. The DEMATEL method is used as a systematic evaluation tool to analyze the extent of mutual influence among the supply chain change factors. On this basis, the prominent factor was identified and the type and extent of factors' role in the AM adoption process were quantified. Supply chain strategy appeared to be the most decisive change factor given its influence on the transition of the tactical and operational elements. The outsourcing of the production activities to 3D printing service providers showed to be another major change factor involved in the AM adoption.

The chapter continued by providing future research directions. We found that conceptual modeling and analysis were the most frequent approaches for exploring AM adoption, particularly in studying supply chain strategy-related topics. The network configuration and facility location aspect of the supply chain has also been well supplied in the AM literature. Besides, there are several quantitative analyses of the inventory- and operations scheduling-related problems. The rest of the aspects explored in this chapter received limited attention in the academic literature and require multidisciplinary investigations to improve the know-how of the logistical support within and after the AM adoption.

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References

Arbabian ME (2022) Supply Chain Coordination via Additive Manufacturing. Int J Prod Econ 243:108318. https://doi.org/10.1016/j.ijpe.2021.108318

Arora R, Arora PK, Kumar H, Pant M (2020) Additive Manufacturing Enabled Supply Chain in Combating COVID-19. J Ind Integr Manag 05:495–505. https://doi.org/10.1142/S2424862220500244

Beltagui A, Kunz N, Gold S (2020) The role of 3D printing and open design on adoption of socially sustainable supply chain innovation. Int J Prod Econ 221:107462. https://doi.org/10.1016/j.ijpe.2019.07.035

Bower JL, Christensen CM (1995) Disruptive technologies: catching the wave

Braziotis C, Rogers H, Jimo A (2019) 3D printing strategic deployment: the supply chain perspective. Supply Chain Manag An Int J 24:397–404. https://doi.org/10.1108/SCM-09-2017-0305

Chan HK, Griffin J, Lim JJ, et al (2018) The impact of 3D Printing Technology on the supply chain: Manufacturing and legal perspectives. Int J Prod Econ 205:156–162. https://doi.org/10.1016/j.ijpe.2018.09.009

Chiu M-C, Lin Y-H (2016) Simulation based method considering design for additive manufacturing and supply chain. Ind Manag Data Syst 116:322–348. https://doi.org/10.1108/IMDS-07-2015-0266

Chopra S, Meindl P (2015) Supply Chain Management Strategy and Operation. Pearson 13–17

Choudhary N, Kumar A, Sharma V, Kumar P (2021) Barriers in adoption of additive manufacturing in medical sector supply chain. J Adv Manag Res 18:637–660. https://doi.org/10.1108/JAMR-12-2020-0341

Corsini L, Aranda-Jan CB, Moultrie J (2022) The impact of 3D printing on the humanitarian supply chain. Prod Plan Control 33:692–704. https://doi.org/10.1080/09537287.2020.1834130

Cui W, Yang Y, Di L, Dababneh F (2021) Additive manufacturing-enabled supply chain: Modeling and case studies on local, integrated production-inventory-transportation structure. Addit Manuf 48:102471. https://doi.org/10.1016/j.addma.2021.102471

Delic M, Eyers DR (2020) The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. Int J Prod Econ 228:107689. https://doi.org/10.1016/j.ijpe.2020.107689

Delic M, Eyers DR, Mikulic J (2019) Additive manufacturing: empirical evidence for supply chain integration and performance from the automotive industry. Supply Chain Manag An Int J 24:604–621. https://doi.org/10.1108/SCM-12-2017-0406

Falatoonitoosi E el, Leman Z, Sorooshian S, Salimi M (2013) Decision-making trial and evaluation laboratory. Res J Appl Sci Eng Technol 5:3476–3480

Fontela E, Gabus A (1976) The DEMATEL observer

Gunasekaran A, Patel C, McGaughey RE (2004) A framework for supply chain performance measurement. Int J Prod Econ 87:333–347. https://doi.org/10.1016/j.ijpe.2003.08.003

Gupta N, Tiwari A, Bukkapatnam STS, Karri R (2020) Additive Manufacturing Cyber-Physical System: Supply Chain Cybersecurity and Risks. IEEE Access 8:47322–47333. https://doi.org/10.1109/ACCESS.2020.2978815

Khajavi SH, Holmström J, Partanen J (2018) Additive manufacturing in the spare parts supply chain: hub configuration and technology maturity. Rapid Prototyp J 24:1178–1192. https://doi.org/10.1108/RPJ-03-2017-0052

Halassi S, Semeijn J, Kiratli N (2019) From consumer to prosumer: a supply chain revolution in 3D printing. Int J Phys Distrib Logist Manag 49:200–216. https://doi.org/10.1108/IJPDLM-03-2018-0139

Hohn MM, Durach CF (2021) Additive manufacturing in the apparel supply chain — impact on supply chain governance and social sustainability. Int J Oper Prod Manag 41:1035–1059. https://doi.org/10.1108/IJOPM-09-2020-0654

ISO/ASTM 52900 (2021) Additive manufacturing — General principles — Fundamentals and vocabulary. PA, USA

Khajavi SH, Partanen J, Holmström J (2014) Additive manufacturing in the spare parts supply chain. Comput Ind 65:50–63. https://doi.org/10.1016/j.compind.2013.07.008

Kunovjanek M, Reiner G (2020) How will the diffusion of additive manufacturing impact the raw material supply chain process? Int J Prod Res 58:1540–1554. https://doi.org/10.1080/00207543.2019.1661537

Li Y, Cheng Y, Hu Q, et al (2019) The influence of additive manufacturing on the configuration of make-to-order spare parts supply chain under heterogeneous demand. Int J Prod Res 57:3622–3641. https://doi.org/10.1080/00207543.2018.1543975

Luomaranta T, Martinsuo M (2019) Supply chain innovations for additive manufacturing. Int J Phys Distrib Logist Manag 50:54–79. https://doi.org/10.1108/IJPDLM-10-2018-0337

Martinelli EM, Christopher M (2019) 3D printing: enabling customer-centricity in the supply chain. Int J Value Chain Manag 10:87. https://doi.org/10.1504/IJVCM.2019.099097

Priyadarshini J, Singh RK, Mishra R, Bag S (2022) Investigating the interaction of factors for implementing additive manufacturing to build an antifragile supply chain: TISM-MICMAC approach. Oper Manag Res. https://doi.org/10.1007/s12063-022-00259-7

Ramón-Lumbierres D, Heredia Cervera FJ, Minguella-Canela J, Muguruza-Blanco A (2021) Optimal postponement in supply chain network design under uncertainty: an application for additive manufacturing. Int J Prod Res 59:5198–5215. https://doi.org/10.1080/00207543.2020.1775908

Rinaldi M, Caterino M, Macchiaroli R (2022) Additive manufacturing and supply chain configuration: Modelling and performance evaluation. J Ind Eng Manag 15:103. https://doi.org/10.3926/jiem.3590

Rogers H, Baricz N, Pawar KS (2016) 3D printing services: classification, supply chain implications and research agenda. Int J Phys Distrib Logist Manag 46:886–907. https://doi.org/10.1108/IJPDLM-07-2016-0210

Santander P, Cruz Sanchez FA, Boudaoud H, Camargo M (2020) Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resour Conserv Recycl 154:104531. https://doi.org/10.1016/j.resconrec.2019.104531

Sasson A, Johnson JC (2016) The 3D printing order: variability, supercenters and supply chain reconfigurations. Int J Phys Distrib Logist Manag 46:82–94. https://doi.org/10.1108/IJPDLM-10-2015-0257

Scott A, Harrison TP (2015) Additive Manufacturing in an End-to-End Supply Chain Setting. 3D Print Addit Manuf 2:65–77. https://doi.org/10.1089/3dp.2015.0005

Silva M Da, Da Silva LCA, Brambilla FR (2020) A bibliographical analysis in the literature of value co-creation in private higher education between the years 2006 to 2016. Indep J Manag Prod 11:1323. https://doi.org/10.14807/ijmp.v11i4.1136

Son D, Kim S, Jeong B (2021) Sustainable part consolidation model for customized products in closed-loop supply chain with additive manufacturing hub. Addit Manuf 37:101643. https://doi.org/10.1016/j.addma.2020.101643

Sonar H, Khanzode V, Akarte M (2022) Additive Manufacturing Enabled Supply Chain Management: A Review and Research Directions. Vis J Bus Perspect 26:147–162. https://doi.org/10.1177/09722629221087308

Strong D, Kay M, Conner B, et al (2018) Hybrid manufacturing – integrating traditional manufacturers with additive manufacturing (AM) supply chain. Addit Manuf 21:159–173. https://doi.org/10.1016/j.addma.2018.03.010

Sun H, Zheng H, Sun X, Li W (2022) Customized Investment Decisions for New and Remanufactured Products Supply Chain Based on 3D Printing Technology. Sustainability 14:2502. https://doi.org/10.3390/su14052502

Thomas A, Mishra U (2022) A sustainable circular economic supply chain system with waste minimization using 3D printing and emissions reduction in plastic reforming industry. J Clean Prod 345:131128. https://doi.org/10.1016/j.jclepro.2022.131128

Ying K-C, Fruggiero F, Pourhejazy P, Lee B-Y (2022) Adjusted Iterated Greedy for the Optimization of Additive Manufacturing Scheduling Problems. Expert Syst Appl 116908. https://doi.org/10.1016/j.eswa.2022.116908