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Additive Manufacturing for Remedying Supply Chain Disruptions and Building Resilient and Sustainable Logistics Support Systems

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Abstract: Leading industries have implemented various strategic initiatives to enhance the resilience and sustainability of their logistics support systems in response to series of unforeseen disruptions that have significantly impacted supply chains (SCs) and incurred substantial costs over the past few decades. It is essential to assess whether incorporating additive manufacturing (AM) technologies into logistics support processes—either as a complementary solution or in conjunction with existing strategies—can effectively reduce vulnerabilities to disruptions in modern, complex SCs. AM technologies that enable the use of business models that use distributed manufacturing, as opposed to centralized manufacturing, have the potential to create significant change in traditional SCs by bringing parts and products closer to the customer. The supply of raw materials necessary for AM production is lower than that of traditional methods. While this provides a cost benefit in the current structure, there are still challenges, such as in testing and final adjustments of printing parameters. AM technologies enable shorter delivery times compared to traditional manufacturing methods while also reducing distribution costs. This not only enhances service levels, but also lowers inventory costs across all stages of the SC. Additionally, AM technologies can help businesses comply with increasingly stringent environmental regulations introduced in recent decades. Both AM-based production and the logistics processes that support it have smaller ecological footprints compared to traditional manufacturing, making it a more sustainable alternative.

Keywords: disruptions in supply chains; additive manufacturing; AM for sustainable development; sustainable supply chains; resilient logistics

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Academic Editor: Giada La Scalia

Received: 12 February 2025
Revised: 11 March 2025
Accepted: 17 March 2025
Published: 20 March 2025

Citation: Keskin, M.H.; Koray, M.; Kaya, E.; Fidan, M.M.; Söğüt, M.Z. Additive Manufacturing for Remedying Supply Chain Disruptions and Building Resilient and Sustainable Logistics Support Systems. *Sustainability* **2025**, *17*, 2783. https://doi.org/10.3390/su17062783

1. Introduction

This study discusses key characteristics that can significantly contribute to the sustainability paradigm. A primary reason for this is that nearly all sectors relying on complex, high-tech systems today require resilient and sustainable SCs to survive in an intensely competitive environment and gain strategic advantages. This article examines the causes and consequences of disruptions in SCs and explores the potential of AM technologies to mitigate their negative effects. These insights directly enhance the sustainability paradigm.

SCs, or, in other words, the logistics support systems of businesses, consist of various stages with different responsibilities, from initial design to delivery of products to the customer and, when necessary, take-back or disposal [1]. Each stage has complicated details that require specialization in more than one discipline other than logistics. SCs have provided a competitive advantage to those who use them effectively, with increasing momentum since the 1950s [2], while contemporary businesses powered by traditional SCs are becoming more sensitive with each passing year due to unpredictable logistics support disruptions. As SC disruptions have emerged as a crucial concern because of some consequences which cannot be overcome, AM technologies may have been introduced as a remedy to cope with them [3–5].

Although AM applications are still far from widespread, for some reasons [6,7], they may have the potential to cope with disruptions in SCs, because AM technologies presently have the potential to provide opportunities to improve engineer-to-order manufacturing [8,9] and allow for production processes involving very various sizes and geometries without the need for traditional complex production systems [10,11] with increasing adaptability, efficiency, and responsiveness [12,13].

The literature on the interaction and application of AM with SCs is quite rich. In a literature review recently conducted by Woldesilassiea et al. [14] investigating the effects of AM on SCs, 978 articles published in peer-reviewed journals from 2004 to 2023 were examined, and it was determined that the applications of AM in developing countries were quite limited compared to industrialized countries. The systematic literature review performed by Kunovjanek and his friends [15] identifies the characteristics and main trends of the impacts of AM on different areas in the SC. In the studies cited in these literature reviews, the relationship between SCs and AM is discussed in general, and it was determined that disruptions in SCs and AM's impact on the future of SCs have not been given as much attention as is necessary. It is also worth noting that studies on post-pandemic applications of AM (e.g., 2023–2024) have been conducted [16–18].

The literature review on production with AM technology in a SC context reveals that research on AM technologies is increasingly concentrated in developed countries. These studies primarily examine the environmental, economic, and social impacts of AM on SCs, highlighting its effects on cost, time, inventory, production, energy consumption, environmental sustainability, and overall firm performance. However, they also indicate that applications of AM in modern SCs face certain limitations, including quality control challenges, production defects, constraints on the range of producible products, restrictions on compatible part types, and issues related to technical and mechanical properties.

There are two different perspectives on the relationship between AM and SCs in terms of logistics. The first one considers logistics support of AM technologies, covering the supply of semi-finished products, raw materials or spare parts, maintenance, shipping, storing, handling, lashing, delivering, etc. The second perspective focuses on using AM to improve SC processes by providing logistics benefits. This article specifically examines the second perspective, exploring how AM technologies impact improvements in sustainability and resilience in SCs. While adopting a holistic approach, the article briefly touches on the causes and consequences of disruptions in SCs, and the AM methodologies developed to date. It seeks to define how integrating current AM methodologies into SC models can enhance sustainability by addressing disruptions within the SC. In this context, the article aims to differentiate itself from previous studies by contributing to the literature and aiding SC managers in various industries facing sustainability challenges.

2. Root Causes of SC Disruptions and Some Events on the Ground

Disruptions faced by SC managers, which have varying negative impacts, can originate from different factors at each stage of the logistics support network, including the following:

- Health crises (e.g., pandemics and widespread diseases);
- Wars, political conflicts, and terrorist attacks;
- Unpredictable and uncontrollable natural disasters, such as earthquakes, hurricanes, floods, wildfires, landslides, and volcanic eruptions;
- Social and economic challenges, including insufficient container supply, labor shortages or strikes, currency fluctuations, inflation, trade disputes, and fluctuations in fuel and freight prices;
- Transportation-related accidents, occurring on roads, railways, airways, or maritime routes during shipping, delivery, or distribution;
- Cybersecurity threats, including value chain attacks and third-party cyberattacks;
- Insufficient handling, transportation, and delivery capacity, including shortages of vehicles, equipment, and infrastructure.

The COVID-19 pandemic has caused disruptions in SCs in almost all industries and sectors around the world at a level perhaps unprecedented in recent years [19]. The pandemic affected global logistics support networks, causing supply problems and workforce limitations in many sectors, especially the automotive industry, forcing production and logistics centers to close and limiting production supply [20]. Although those were not permanent, they had very solid impacts which could be felt on a global scale throughout and after the epidemic. For example, after COVID-19 reached the U.S. in mid-March 2020, economic activity, as measured by real GDP, contracted at an annualized rate of 5% in the first quarter. This decline accelerated to a staggering 32% in the second quarter due to government-mandated quarantines, marking the COVID-19 crisis as the fastest and most severe economic shock in modern U.S. history [21]

Wars, political conflicts, and terrorist attacks are other causes of SC disruptions, having led to food and energy supply disruptions that came to the fore with the Russian–Ukrainian War [22,23]. Ukraine's economic output is now at a fraction of its pre-war levels. In the first year of the conflict, the country lost 30–35% of GDP. This led to the largest recession in Ukraine's history [24]. Such interruptions are mostly limited to the area of influence of the region where wars, conflicts, and terrorist attacks occur.

SC disruptions occur [25–27] following the occurrence of unpredictable and uncontrollable disasters such as earthquakes, hurricanes, floods, forest fires, landslides, volcano eruptions, etc. The eruption of the Eyjafjallajokull volcano in Iceland on 14 April 2010, is a good example. Due to the ash cloud rising more than 3 km after the explosion, air traffic in European airspace was stopped, and more than 100 thousand flights were canceled. International trade, especially of perishable goods, and just-in-time production processes have also been severely disrupted. While some disrupted trade might be delayed, this is not the case for quickly disappearing produce or just-in-time production components such as fresh-cut flowers, vegetables, and exotic fruits. Food producers in African countries such as Kenya, Zambia and Ghana were negatively affected as well. The cost of flower exports from South America to Europe alone for producers was approximately USD 3 million. The total GDP loss between 15 April and 24 May 2010, was almost USD 5 billion. Korea International Trade Association said losses in domestic industries were estimated at USD 112 million between 16 and 19 April, while mobile phone and semiconductor suppliers were hit the hardest. Automobile production lines in Europe and Asia suspended production due to major components not reaching factories [28].

Another example is the Tōhoku earthquake and subsequent tsunami that occurred in Japan in 2011 [29,30], which directly affected many SCs of varied industries. With the disaster, in which nearly 500 businesses in the service sector went bankrupt, nearly 800 production centers and wholesale service players had to withdraw from the SC. As a natural consequence, global SCs were disrupted, especially in electronics and the automotive industries. Global brands such as Toyota, Honda, and Sony were unable to obtain spare parts and raw materials due to the interruption in their SCs and had to stop their production [31].

Hurricane Katrina, which occurred in 2005, was one of the deadliest and costliest hurricanes in US history. It resulted in a solid negative impact on SCs. The hurricane caused widespread destruction, particularly in the Gulf Coast region; it disrupted oil and gas production, transportation infrastructure and ports, and led to nationwide shortages of fuel, raw materials, and consumer goods [32].

SC disruptions may also occur due to social and economic issues such as congestion at ports, insufficient container supply, employment problems or labor strikes, currency fluctuations, inflation or trade disputes, and changes in fuel and freight prices. The USA, the UK, France, South Korea, and Spain are also among the countries affected by transportation strikes. The impacts of these strikes was experienced in all modes of transportation, including air, rail, road, sea and port, and maritime transport. Strikes by pilots and ground crews have caused flight cancelations and chaos in Europe and the US. Since commercial flights carry significant cargo shipments, cancelations resulting from airport strikes also affect air cargo space and rates. Major rail strikes introduce threats to rail transportation in the US, and could potentially cost USD 160 billion per day. Although heavy industry manufacturers are direct end customers, they are dependent on railways in the SC. Truckers protesting the coronavirus vaccine requirement at the US–Canada border blocked border crossings, including the Ambassador Bridge between Detroit, Michigan, and Windsor, Ontario, affecting 25% of all trade between the US and Canada. Losses amounted to approximately USD 1 billion per day. Deliveries of critical auto parts were delayed by about a week [33].

Due to accidents occurring in means of transportation or on roads, railways, air, or maritime transport during shipping, delivery, or distribution, it is also possible that SCs will be disrupted. Recent events, such as the collapse of the Baltimore Bridge, brought the sensitivity of disruptions in SCs back to the top of the agenda [34]. US Transportation Secretary Buttigieg had warned of the major and long-lasting impact closure of the Port of Baltimore, following the bridge collapsing, would have on the SCs of certain regions and industries. Even US President Biden felt the need to make a statement, and described the bridge as "one of the most important elements" supporting the economy in the northeastern US. The port of Baltimore, which closed after the collapse of the bridge, is the ninth busiest port in the USA in terms of car shipments, handling at least 750,000 vehicles a year, including Volkswagen and BMW. Motor vehicles and parts account for 42% of all Baltimore port imports. The port handled USD 80 billion worth of foreign cargo in 2023, meaning that it will lead to millions of USD in trade and tax losses if everyday shipping ships are blocked from accessing it. Since the distribution warehouses owned by Amazon and FedEx are in this port, some of their operations were also interrupted. Baltimore is the second busiest port for US coal exports. The collapse of the Baltimore Bridge could affect the volume of coal exported from the US, potentially having a major impact on people making bricks in India [35]. That a collapsed bridge in the US have a negative impact on production processes in India indicates the integrated structure of global SCs and their sensitivity.

Evergreen, which crashed into the Suez Canal while passing through, is one of the best examples of SCs being blocked due to accidents. About 8 percent crude oil (about one million barrels) passes through the Suez Canal every day, one of the busiest shipping lanes of the world, which accounts for 12 percent of the world's trade. The blockage of this vital waterway caused traffic to halt, leading to delays in the delivery of goods, increased shipping costs, and disruptions to worldwide SCs. The blockage is estimated to have hindered approximately USD 9.6 billion worth of trade daily. This means that 3.3 million tons per hour cannot be shipped due to the blockage. Due to the impact of the congestion, annual trade growth also fell between 0.2 percent and 0.4 percent. Moreover, many ships were diverted to avoid crossing the canal, causing delays of more than a week in their journeys. Problems also began to be experienced in the supplying of empty containers. While there were delays in the transporting of cargo of Asian companies coming from Europe due to the traffic congestion caused by the accident, the impact of this was felt mostly in Europe. The countries that were most affected by this crisis include England, Belgium, Netherlands, France, Germany, Italy, Spain, Switzerland, Türkiye, and Austria. While the most affected sectors in Europe were the food, chemical, medical, construction, equipment, metal, and automotive industries, the sectors most affected by the blockage in the USA were as follows: food, hardware, household appliances, automobiles, medical equipment, heating and air conditioning, trucking, and sporting goods [36,37].

Another reason for disruptions is cited as cyber-attacks, which are called value chain attacks or third-party attacks as well, aimed at preventing the functioning of SCs. Third-party players in SCs, also called outsourcing suppliers, are often targeted in SC cyber-attacks. An attacker inserts malicious code (or 'malware') into the software used by those who manage the SC, which can then be transmitted to the customer who purchases the end-product. In the SolarWinds attack in 2020, 18 thousand customers were targeted [38]. More than 10 million people were impacted by SC attacks targeting 1743 entities that had access to multiple organizations' data in 2022. Based on an IBM analysis, the cost of data breaches averaged USD 4.45 million in 2023. In May 2023, Progress Software's MOVEit file transfer tool (MOVEit Mobile 2.0) was targeted with a ransomware attack. This attack allowed threat actors to steal data from customers using the MOVEit app, including government agencies and businesses worldwide [39].

Insufficient capacities and numbers of handling, transportation, and delivery vehicles and amounts of equipment may prevent SCs from functioning as expected. The problems encountered in the supply of empty containers in recent years are among the first examples that come to mind in this regard. Global shipping companies, such as ocean carriers, have been facing some serious challenges, or disruptions, in maritime logistics recently [40]. These difficulties have led to large increases in freight rates due to container supply disruptions [41]. This fact implies that disruptions in the SC cause a significant increase in freight rates and leads to negative impacts on sustainable SCs worldwide [42]. Congestion at ports, the hubs connecting global production and consumption [43], has recently emerged as a factor causing disruptions in SCs. Port crises have led to SCs, uncertainty, and instability in global container shipping and maritime logistics. Port congestion is an obstacle to smooth SC operations [44], because it is faced whenever the capacity of a port is not sufficient to accommodate ships arriving at that port. SCs have experienced significant delays in shipping and distribution and increased logistics costs due to that. The global trade costs of a ship that cannot unload or load its cargo may lead to loss or disruption of trade. But, it can sometimes reach irreparable levels, depending on the cargo and the vessel. Southeast Asian ports encountered threefold freight rates in late 2021, in comparison with the first half of the year, due to severe US port congestion that was caused, in part, by booming market demand after the onset of the COVID-19 pandemic [45].

The complex structure of SCs may cause interruptions or slowdowns in their smooth and sustainable flow for reasons other than those mentioned above and depicted in Table 1, such as unforeseen restrictions imposed by customs and trade tariffs, large-scale financial cut-backs at the global level, large-scale and long-term power outages, interruption of the energy supply, sudden changes in consumer preferences unlike any before, environmental restrictions, etc.

Table 1. Summary of cases of SC disruptions and implications.

The eruption of the Eyjafjallajokull volcano in Iceland	The cost of flower exports from South America to Europe alone, for producers, was approximately USD 3 million. The total GDP loss between 15 April and 24 May 2010 was almost USD 5 billion. The Korea International Trade Association said losses in domestic industries were estimated at USD 112 million.
Tōhoku earthquake and subsequent tsunami in Japan	With this disaster, in which nearly 500 businesses in the service sector went bankrupt, nearly 800 production centers and wholesale service players had to withdraw from the SC. As a natural consequence, global SCs were disrupted, especially in the automotive and electronics industries.
Hurricane Katrina	Widespread destruction, particularly in the Gulf Coast region; it disrupted oil and gas production, transportation infrastructure and ports, and led to nationwide shortages of fuel, raw materials and consumer goods.
Major rail strikes	The rail transportation sector in the US faced a potential cost of USD 160 billion per day.
Blocked borders by truckers between the US and Canada	It affected 25% of all trade between the US and Canada. Losses amounted to approximately USD 1 billion per day. Delivery of critical auto parts was delayed by about a week.
Collapse of the Baltimore Bridge	Baltimore Port handled USD 80 billion worth of foreign cargo in 2023, meaning that the collapse lead to millions of dollars in trade and tax losses for everyday shipping ships which were blocked from accessing it.
Incident of Evergreen (the Suez Canal)	The blockage is estimated to have hindered approximately USD 9.6 billion worth of trade daily. This means that 3.3 million tons per hour could not be shipped because of the blockage. Due to the impact of the congestion, annual trade growth also fell between 0.2 percent and 0.4 percent.
SolarWinds attack	More than 10 million people were impacted by SC attacks targeting 1743 entities that had access to multiple organizations' data in 2022. Based upon an IBM analysis, the cost of data breaches averaged USD 4.45 million in 2023.

3. Consequences of SC Disruptions

SC disruptions have varied consequences that affect all stakeholders interacting within all logistics processes, from the design phase or raw material procurement stage, which are mostly considered the initial steps of a SC, to the delivery of the final product, or reverse logistics phase. It is not always possible to prevent disruptions in SCs in global networks. While some issues can be resolved through operational interventions, others may be irreparable. Given the complex nature of the highly competitive global market, it would be unrealistic to expect any company to manage all potential disruptions. So, SC managers must be ready to face a variety of challenges and develop resilience by learning to mitigate the risks of potential outcomes. Considering the extensive literature on SC disruptions, consequences are briefly mentioned here without going into detail.

While fierce competitive pressure is increasing day by day at the global level due to the rapid increase in consumption and production [46], one of the significant tools to reduce costs to ensure competitiveness is the effective management of the SC. Accordingly, SC interruptions, especially in the production and distribution processes, cause costs, in overtime wages for workers and sourcing from more expensive suppliers, to increase, not decrease. In high-budget SCs, the responsibilities and expectations of involved parties are outlined in detailed contracts. SC outages may lead to unfulfilled responsibilities, customer loss, legal sanctions, and financial penalties. Consequently, these outages can often result in reputational damage and loss of revenue [47]. Globalization, which started after World War II, especially after the end of the Cold War with the fall of the Berlin Wall in 1989, led to the dominance of the capitalist system in the global market. The producer-oriented market has evolved into a consumer-oriented market. Global brands, which have been designing their SCs according to customers' demands [48–50] for more than 4 decades, began to face significant customer dissatisfaction and even customer losses whenever there was a SC interruption. Dissatisfaction with the failures of SCs is not limited to the customer side, but is also seen in all SC players, especially raw material and semi-finished product suppliers. One of the first consequences of SC disruptions to come to mind is interruptions and slowdowns in production due to problems in the supply of raw materials, components, or final products. It is inevitable that there will be delays in delivering the final product to the customer [51]. Disruptions in the SC can lead to regulatory compliance issues, especially in industries such as ADR with stringent quality or safety standards. Failure to meet regulatory requirements due to outages may result in failure to fulfill legal obligations or damage to corporate reputation. Even so, the JIT philosophy, known from the zero-stock motto and spread from Japan in the 1960s, was based on the basic design of all SCs. In it, a stock is kept at a minimum level at every stage of the SC for smooth operation [52]. Disruptions in the SC cause stocks to fall below sustainable levels [53]. Although stockout costs vary depending on the sector in which the SC operates, they can often reach significant levels because of the costs of working capital, storage costs, and the costs incurred by spoilage of perishable goods. Long-term SC outages can cause significant operational downtime for manufacturing centers, warehouses, and distribution stations. This interruption may cause additional costs, such as those incurred by the existing production capacity remaining vacant and the costs of initiating production again. Due to the complexity of global business, SC disruptions cause many effects, such as increasing freight rates, decreasing production quality, and having to produce with higher energy costs, in addition to those mentioned above. SC managers, welcoming benefits from hi-tech tools such as artificial intelligence and its derivatives, make up their minds regarding long-term strategic decisions to shift in their SC designs to cope with SC disruptions.

4. Exploring Additive Manufacturing

AM technologies enable the production of large numbers of parts at any time and place using a single machine. The first applications were seen in the 1970s [54]; AM may, today, provide opportunities that can help SCs achieve their goals and potentially eliminate their disruptions. It enables the assembly of parts made of the same material to be produced as a single piece, which reduces or eliminates cost, time, and quality problems arising from assembly processes compared to the classical production approach [55,56].

Although the terms 3D printing and AM are often used interchangeably, it is important to note that they have distinct differences in meaning and application. Three-dimensional printing typically refers to smaller-scale processes used by individuals or small businesses, while AM is a broader industrial term that refers to the same process of building objects layer by layer, but on a larger, more complex, and high-performance scale. AM involves a wider range of materials, including metals, and is used in industries that require high precision, strength, and durability, such as aerospace, automotive, healthcare, and construction. Because AM is applied in critical industries, it must meet stringent regulatory and certification standards to ensure safety, quality, and performance compliance. In essence, all 3D printing is a form of AM, but not all AM is considered 3D printing.

AM technologies differ from traditional ones, with some features that provide some advantages. Unlike traditional subtractive manufacturing methods, where material is cut from a solid block, AM products are created by adding materials layer by layer to produce a three-dimensional object. AM technologies can work with a wide variety of materials, including plastic, aluminum alloys, titanium alloys, stainless steels ceramics, and even biological materials such as cells and proteins [57]. Generally, four different technologies are used for AM; those are Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS). In FDM technology, the most common type of AM technology, a thermoplastic filament is heated and extruded layer by layer through a nozzle to form the object. SLA technology uses a vat of liquid photopolymer resin that cures with ultraviolet (UV) light to create layers and a UV laser to trace the pattern of each layer. SLS and DMLS technologies are similar. SLS is mostly preferred in the production of materials whose raw materials are plastic or metal. A high-power laser combines powdered material to form layers of the object. DMLS, on the other hand, is preferred for the creation of metal parts; metal powder particles are sintered layer by layer with laser [48]. Following production processes designed using computer-aided design software, products are designed in thin layers and then produced by printing the layers on top of each other. Apart from the optimization and savings associated with shorter delivery times and reduced stock requirements, it contributes to a more sustainable economy by minimizing waste [57]. Due to AM technologies, complex geometries and complex designs that are difficult or impossible to produce with traditional methods can be easily produced. Since AM technologies use a kind of additive process, they produce less waste than traditional methods. A cost advantage, although relative, can also be gained through mass production [58,59]. With AM, products can be produced on demand, reducing the need for inventory storage and providing flexibility in meeting customer demands [48]. Because of AM, instead of reaching an optimally efficient product through trial and error with the parts produced, analyses can be carried out through computer programs without loss of materials and work [60]. Another crucial aspect of this manufacturing method is the significant reduction in the weight of parts produced through designed lattice structures, compared to those produced by other equivalent methods. It boasts significant advantages, including efficient raw material utilization, and allowing for the creation of structures with exceptionally small sizes and intricate geometries; industries such as those of the defense, aerospace, space exploration, molding, chemical, healthcare, marine, and automotive sectors favor this approach for producing costly materials made into complex structures [61].

Although the dynamics of the AM technologies mentioned above offer advantages that could significantly help mitigate SC disruptions, they still have certain disadvantages that cannot be entirely overcome, preventing them from fully replacing traditional production methods. While the variety of materials that can be produced with AM technology increases day by day, it is not yet possible to use AM with some materials suitable for traditional production processes. Difficulties may be encountered in achieving high surface roughness and resolutions with AM technologies. Therefore, depending on the technology and material used, a second correction may be required before delivering the product to the customer. If the materials to be produced are large or complex in scale, production may take longer than traditional production methods. Another disadvantage of AM technologies is the possibility of causing changes in the microstructure of the material during operations such as machining, laser cutting, or welding. The rapid heating and cooling cycles used in laser-based AM can create residual stresses, which may result in warping, cracking, or distortion in the final product. AM processes can alter grain size, texture, and phase distribution, causing inconsistent mechanical properties—a critical concern in industries like aerospace and medical implants, where uniform material performance is essential. Additionally, high-energy lasers can lead to gas entrapment, keyhole formation, or incomplete fusion, increasing porosity, which weakens the material and reduces fatigue resistance. Changes in the microstructure may also introduce brittle phases, reduced ductility, or uneven hardness, negatively impacting the material's strength and durability. Furthermore, laser-based AM methods create a heat-affected zone, where thermal alterations can weaken the structure or cause undesirable phase transformations. To address these microstructural inconsistencies, post-processing techniques such as heat treatment, hot isostatic pressing, and machining are often required, adding extra time and costs to production. While optimized process parameters, controlled cooling rates, and post-processing methods can enhance material properties and reduce defects, it is not possible to eliminate these issues entirely.

Considering that the same product produced in different centers under different external conditions may exhibit variable behavior under operating conditions, it can be said that the probability of a change in the function of the product after its delivery to the customer is higher than in traditional methods [62].

5. Recalling Supply Chains

SCs, which garnered increasing interest after World War II, are a logistics structure that supports every stage of production processes, regardless of scale and sector. It is now much more than logistics. In today's customer-oriented market dominated by fierce competition, it is necessary to have a good SC and manage it well—not just with regard to making money, but also ensuring survival. Briefly, SCs are integrated processes in which suppliers, manufacturers, distributors, and dealers work together through stages starting from the design to the delivery of an end-product to customers, before going on even to the recycling phase. Although quite complex, with trans-oceanic dimensions, SC processes support three main stages: procurement, production, and distribution, which can be broken down into smaller parts, as shown in Figure 1. Procurement support covers the set of activities related to meeting demands for raw materials and semi-products. Production support involves all actual production processes involving logistics, where raw materials are transformed into final products. The last stage, distribution support, refers to the support of transactions, aimed at delivering final goods to the consumer [48,63,64].

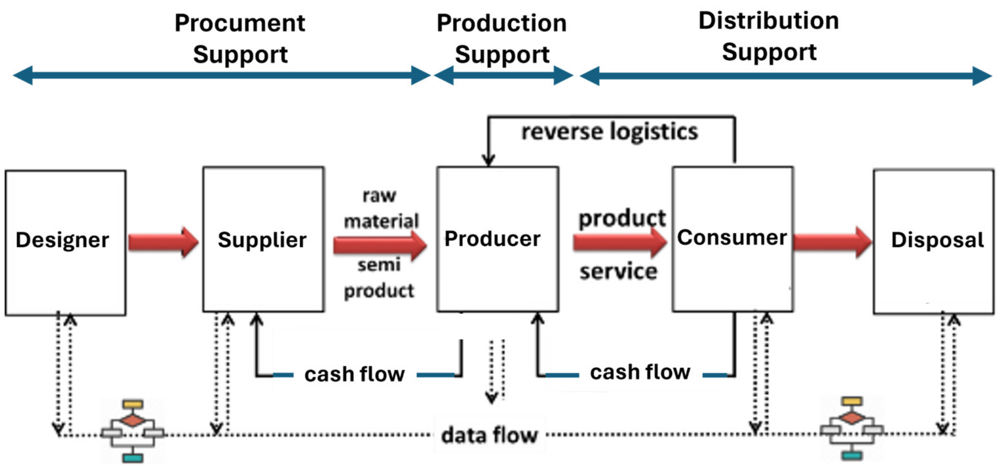

Figure 1. A conventional supply chain [2].

Given that today's high-tech vehicles, such as large ships, trucks, aircraft, cranes, and other equipment, as well as monitoring devices, software, and other technologies have evolved significantly, contemporary SC procedures have become complex, spanning multiple disciplines and requiring professional skills and competencies.

6. Coping with the Consequences of Disruptions in SCs

Coping with SC disruptions has become a primary concern due to their significant costs. The precautions for SC disruptions can be classified into the following three categories: the measures to be taken before, during, and after a disruption occurs. Experience in the field indicates that proactive measures are quite effective in creating resilient SCs that can effectively cope with possible disruptions. SC managers should have a good overview of their company's logistic structure, and its strengths and weaknesses. Since most large-scale disruptions occur due to sudden and unforeseen causes, the biggest challenge is predicting risks. Making a list of the risks involved may be helpful in understanding the situations in which businesses become vulnerable. Adhering to this list, and penning a proactive, detailed, and fact-based risk plan, to be carried out in advance, may be an extremely useful tool. A close relationship with all SC players, including suppliers, customers, and employees, can be a significant contribution, by creating a common sense of support between all parties in solving problems. It is important to communicate effectively with them to catch early signals of significant disruptions as well. Strengthening outsourcing and increasing the number of third-party suppliers in various landscapes and different political regions can be considered as another measure. Ensuring supply security and having a smooth way to obtain raw materials and semi-finished products to prevent a lack of vital necessities, such as transportation, distribution, storage, and handling, may enhance sustainability. Cash power can be a leveraging tool to purchase goods and services, as the cost of what is needed can rise suddenly during and after a crisis. The most common issue faced during crises is a lack of or insufficiency of inventory. The precautions taken to prevent this may lead to success if optimal levels are kept in inventory. Otherwise, unnecessary stock accumulation, which has caused classic inventory issues after crises, is inevitable. The burdens of unnecessary storage being spoiled, or obsolete products' costs may exceed those of the crisis. The need for smooth and effective software with complex SC structures becomes more evident in crises. Effective management with instant information at each stage of a complex SC structure, from transportation to inventory, distribution, storage, demand forecasting, and capacity planning, is only possible with software and systems supported by AI [15].

In addition to the points mentioned above, effectively facing and coping with possible disruptions requires identifying factors that may cause SC disruptions and conducting realistic risk assessments. Utilizing artificial intelligence-based tools can help minimize the impact of potential disruptions, while real-time monitoring of all logistics support processes ensures end-to-end SC visibility, including the use of digital twin applications where possible. Diversifying suppliers and sourcing regions for raw materials and semi-finished products is essential, along with establishing rational safety stock levels. Additionally, developing alternative transportation and distribution strategies enables businesses to adapt to potential changes and maintain SC resilience.

7. Integrating AM to Enable Sustainable and Resilient SCs

Since many outages occur due to unforeseen reasons, according to experience, even with all the precautions mentioned above, it is not entirely possible to evade the effects of outages. Therefore, looking for ways to implement AM technologies within logistics support systems [65] may enable SCs to become not only more resilient, but also more sustainable.

As AM technologies enable the production of varied types and shapes of products in remote locations [66,67], like the distribution centers (DCs) in traditional SCs dispersed across different geographical regions, a variety of low-volume, high-customization, high-urgency SC structures have emerged as needed for logistical support of these production processes.

The relationship between AM and SCs can be viewed in two different dimensions. The first one covers the logistics support of the machines used in the production of AM technologies (Figure 2a), the provision of semi-finished products and raw materials used in AM production processes, and the supply of spare parts required for maintenance support of AM processes. The other is to use AM processes to support SC processes to provide logistical benefits (Figure 2b). Since this manuscript focuses on how AM processes can be used to make SCs more durable and sustainable, it focuses on the second dimension, that is, in which parts of SCs AMs are used.

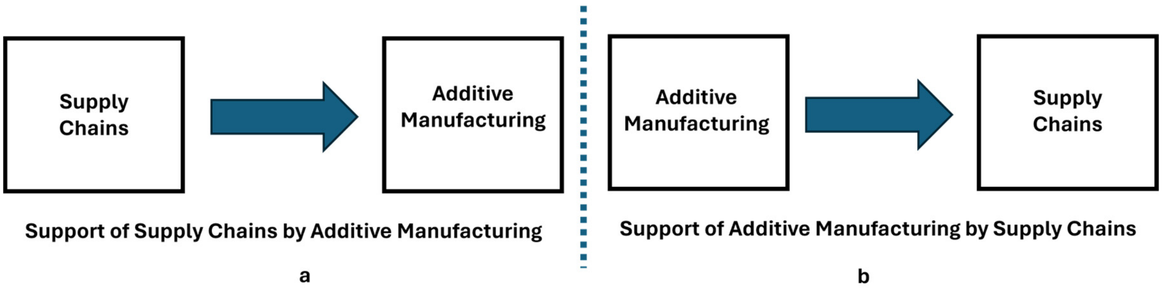

Figure 2. (**a**,**b**) The relationship between AM and SCs.

The fact that SCs have the potential to provide a cost-effective advantage over competitors when created and used effectively is among the main reasons why SCs are attracting accelerated attention. By incorporating AM technologies into SCs, their contribution can be significantly enhanced, potentially reducing transportation and packaging costs compared to traditional SCs. AM technologies that enable business models that use distributed manufacturing, as opposed to centralized manufacturing, have the potential to create significant change in traditional SCs by bringing parts and products closer to the customer.

SC decision-makers looking to transition from traditional, centralized production to distributed AM technologies should follow a structured approach. First, they must conduct a realistic feasibility study of AM processes, evaluating their potential and limitations. This involves developing a model that prioritizes key factors such as quality, intellectual property rights, and customer satisfaction, while ensuring a sustainable process framework. At every stage of the SC—including storage, inventory management, transportation, distribution, and handling—logistics processes must be optimized to align with the decentralized nature of AM. Given the typically lower production volumes compared to traditional manufacturing, production requirements should be carefully adjusted to maximize efficiency. Additionally, fostering strong collaborations with raw material suppliers, semi-finished product providers, and outsourcing partners will be essential to ensuring a stable and efficient transition to AM.

To allow for scaling of AM technologies without straining local resources or increasing costs, a three-pillar strategy focusing on efficiency, cost, and sustainability should be adopted. Within this framework, priority should be given to sourcing raw materials and semi-finished products locally whenever possible. Opting for recyclable materials not only minimizes environmental impact and costs, but also enhances sustainability. Applying standardization—one of the key principles of logistics—to AM production processes helps streamline logistics operations. Cost-effectiveness should always be a fundamental consideration in AM applications, as it is essential for achieving low-cost production and affordable products. Since fully transitioning to AM technologies at an early stage may not be feasible due to technological limitations and market dynamics, a hybrid approach that integrates traditional manufacturing methods can help reduce costs. Additionally, outsourcing and leasing can mitigate the need for large upfront investments, thereby lowering the overall financial burden.

These strategies should be implemented to minimize waste, reduce energy consumption, and promote circular economy practices to balance efficiency and sustainability in production processes supported by AM technologies. Prioritizing the use of recyclable and bio-based materials, such as recycled powders and biodegradable polymers, enhances material efficiency and reduces waste, ultimately improving production efficiency and mitigating environmental impact. By enabling the reuse of excess or defective products in re-production processes, AM technologies contribute to both efficiency and sustainability. The integration of AI-driven algorithms further optimizes these processes, enhancing productivity and resource utilization. The expected benefits of AM vary by industry. In the aviation and automotive sectors, for instance, lightweight components are preferred to improve fuel efficiency and lower emissions. In construction, durability is a priority, with sustainability being achieved through the use of degradable or recycled materials. In the medical sector, AM technologies help reduce biological waste and minimize errors in the production of high-cost implants and prosthetics. Additionally, AM technologies facilitate localized production, reducing transportation-related emissions. By integrating AM with sustainable practices, industries can enhance efficiency, minimize environmental impact, and align technological advancements with global sustainability goals.

According to Laplume et al., although the general opinion is that AM will become widespread at the household level [68], it is necessary to evaluate the possibility of it only being preferred in larger-scale SCs. Although investments in AM technologies are quite high at the current technological level, depending on the speed of progress which will be achieved over time, this disadvantage may disappear, and a very high number of players will enter SCs as actors in this sense in the coming years. Another cost advantage for manufacturers using AM technologies is that the necessary supply of raw materials for AM production is lower than for traditional methods. While this provides a cost benefit in the current structure, there are still challenges, such as testing and final adjustments of printing parameters [69]. Another aspect of the cost advantage of producing with AM technologies, along with them being able to produce closer to the target market, is that they have shorter delivery times compared to traditional methods. This ability of AM technologies allows for reductions in marketing time, and reduces the costs of distribution [48]. In this way, in addition to providing a higher level of service, they reduce inventory costs at all SC stages [70]. Using AM technologies can make it easier to meet environmental demands and restrictions that have begun to be regulated by law in the last few decades. Production using AM technologies and the logistics processes that support them leave smaller ecological footprints compared to traditional production methods [71,72]. There are also studies that indicate that AM technologies can help with the global increase in humanitarian needs [73].

AM technology is supposed to make a significant contribution to overcoming various SC disruption challenges, such as administrative constraints, political barriers, and technical obstacles encountered at national borders. AM systems may offer a solution to overcome the negative aspects of protective barriers arising from the trade diversionary effects of customs unions. To illustrate this concept with an extreme example, consider the logistics of shipping weapons to an area experiencing active conflict. Although it is impossible to transport the weapon to a conflict zone, additive manufacturing machines can enable on-site production if sufficient raw material logistics are available for the weapon's production. This example highlights that the reshaping of SCs, in addition to additive manufacturing systems, can lead to new regulations in various fields such as politics, social dynamics, economics, and security [2].

AM technology can help manage the complexities of SCs in rapidly changing and unpredictable environments, particularly in emerging markets, due to its flexibility, speed, and localized production capabilities. By enabling production closer to demand points, AM simplifies and strengthens SCs, reducing the sustainability risks associated with global logistics. In emerging markets, localized production helps lower transportation costs and shortens delivery times. AM also plays a crucial role in implementing the just-in-time (JIT) philosophy, a key principle in efficient logistics. By allowing on-demand production, AM enhances SC responsiveness, reducing the need for large-scale warehousing, and minimizing delays caused by unpredictable market fluctuations. Additionally, AM enables rapid design, testing, and iteration of products, ensuring that businesses can quickly adapt to changing customer demands. This prevents unnecessary stockpiling of spare parts, semi-finished goods, and finished products in warehouses. Moreover, AM reduces the time and costs associated with maintenance processes, easing the financial burden on businesses while improving overall efficiency.

The aviation industry, a pioneer in many disciplines and sectors, also leads in various logistics applications. There are many studies on SCs that support the aviation industry, as the costs of errors or interruptions in the supply of spare parts, maintenance, and repair processes are very heavy and often irrecoverable. An aircraft produced with today's technology by two giant aircraft manufacturers, Boeing and Airbus, consists of approximately 4 million parts, which makes inventory management difficult with traditional SC structures [74,75]. According to Walter et al. [76], who argue that it is more logical to use AM in these processes, in particular, non-standard parts other than those that are replaced at regular intervals according to a maintenance plan are rarely needed, and keeping these parts, called slow-moving parts, in storage is unnecessary with the risk of obsolescence. This causes capital allocation towards and increases logistics costs arising from storage. The AM production solution allows users to both reduce stock levels and to fully utilize the production capacity of AM machines. According to Busachi et al. [77], AM is more likely to be preferred in the EU and US markets, which focus on small-sized but high-value-added products, in which sustainability is difficult.

Despite the many advantages of AM technologies mentioned above, there are also some problems that hinder the full implementation of AM technology, at least for now. These include the fact that the physical dispersion of AM production devices and support equipment across geographically distant locations [78] makes it difficult to perform periodic maintenance on them, along with challenges meeting urgent repair needs and supporting 'make-to-order' spare parts. So, maintenance costs are much higher than those of traditional SCs. Another disadvantage of AM technologies is the difficulties in transportation planning and the lack of the cost efficiency provided by large-scale shipping [79–81]. In SCs that support traditional manufacturing processes, all materials are transported in giant ships, long trains or FTL trailers, etc., to DCs, significant transportation savings are achieved just before last-mile delivery. Optimizing transportation costs is more difficult in AM than for traditional SCs because AM production centers are dispersed across various geographical locations, negating this advantage. The extremely high initial investment and operating costs of AM machines are among the difficulties faced in practice [82]. Furthermore, in cases where outsourcing cannot be achieved, difficulties such as the lack of a skilled workforce to operate AMs and the high cost of this labor should also be noted. Compared with traditional technologies, AM does not provide economies of scale benefits, because the production speed is still poor, and the production capacity is limited [83]. The other disadvantage of AM is the restrictions on dimensions and production times. Compared to traditional techniques, AM processes are relatively slow. Although there is no waiting time between production runs, the total production time is longer than the production times of traditional processes. As a result, traditional production remains the preferred method of construction unless it is possible to increase printing speed if large quantities are needed [84]. SC managers can adopt several measures to effectively cope with decentralized production using AM technologies. One of the most important measures to cope with decentralized production using AM technologies is to create a system for SC managers to replace the manufacturing on demand system. Switching to digital inventory management can help with this transition. AM technologies require the establishment of regional production centers. These structures make it difficult to control product quality relative to traditional production centers. Creating real-time monitoring methods can help overcome this challenge. Prioritizing optimization at every stage of SC processes, using data analytics and AI-powered tools, can contribute to this. It is also necessary to be prepared for issues such as workforce training and intellectual property issues. Finally, in order to overcome the negative impacts on the environment in production processes, it is necessary to select raw materials and semi-finished products from recyclable materials and to minimize production waste.

AI-driven manufacturing processes have the potential to enhance performance, efficiency, and safety through advanced computational techniques such as machine learning and deep learning [85]. AI can improve decision-making and optimize the operational effectiveness of AM technologies [86] by automating various tasks, including SC processes. In manufacturing, AI advancements have extended beyond prototyping to direct production [87]. These developments have enhanced real-time quality monitoring, error detection, cost reduction, and competitiveness, contributing to more sustainable AM production processes. Future advancements will likely focus on human–machine collaboration, workforce skill development, and the integration of advanced technologies to maximize efficiency and productivity. However, despite these benefits, AI applications face challenges such as data bias and research scope limitations, underscoring the need for further exploration of their impact on specific industries and strategies to address these challenges.

The holistic advantages of SCs incorporating AM technologies indicate that they will provide significant benefits in dealing with the disruptions encountered in the functioning of SCs that support traditional production. Although the disadvantages arising from certain financial, administrative, technical, and structural problems have not yet been eliminated, considering the magnitude of the costs of what happens when SCs are interrupted, restructuring SCs with the inclusion of AM technologies can be a remedy in this sense.

In today's traditional SCs, a portion of DCs which are established at certain central points in order for them to be closer to the market or customer, according to the logistics dynamics of the region, market, or industry, can be gradually converted into production and logistic centers which are supported by AM technologies. A structure for the near future of SCs, to be created with AM support, is shown in Figure 3 [2].

This structure will make it easier to face and cope with possible interruptions. As mentioned before, due to AM technologies, highly complex traditional finished-product delivery processes are to be replaced by raw material transportation processes that require much simpler shipping planning and execution.

There will continue to be a need for DCs to supply raw materials or semi-products that are optimally distanced from 3D printer locations. Despite the transformative nature of contemporary SCs, storage will continue to be vital to support the globally distributed SC network.

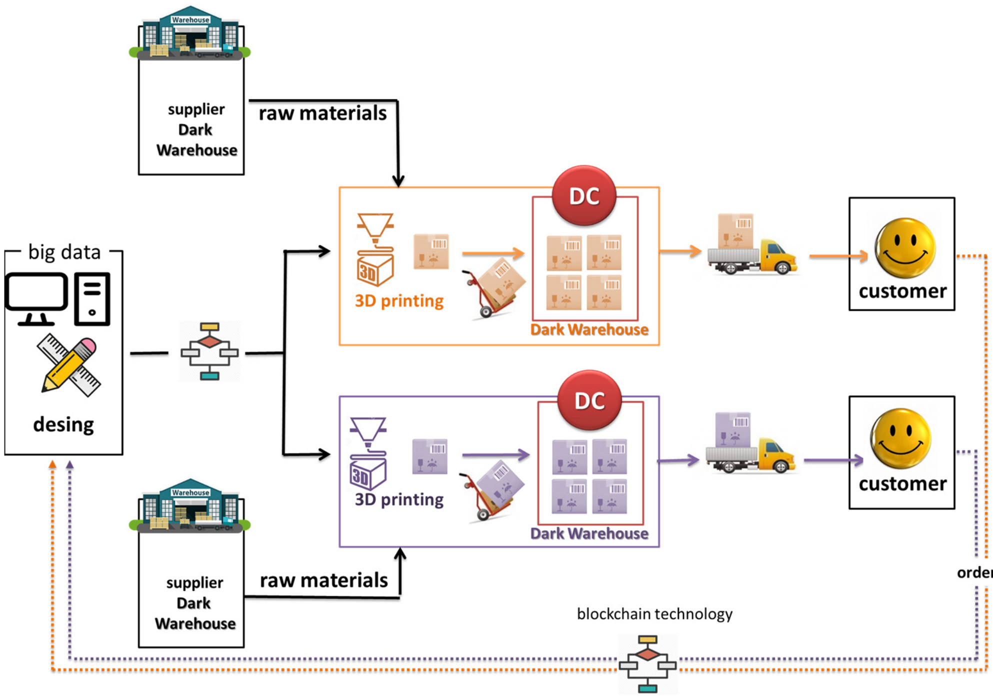

Figure 3. Integrating AM for sustainable and resilient SCs [2].

An approach to addressing this issue using AM technologies during an SC outage is presented in Figure 4a,b. According to the risk report prepared by SC decision-makers, semi-finished products expected to be unavailable during an SC outage can be produced using AM technology to ensure the continuity of the production process, as is depicted in Figure 4c. While this solution may still present several practical challenges, proactive preparation will mitigate costs and disruptions associated with the outage.

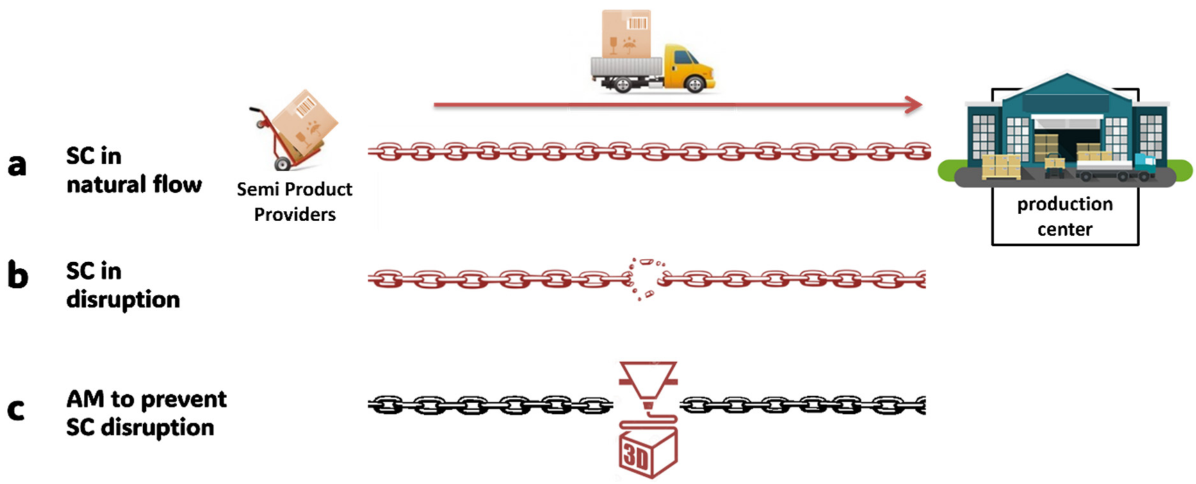

Figure 4. Integrating AM in the case of SC disruption.

However, the AM-supported structure that Sonar et al. [88] showed in Figure 5, which they created after a literature study of 116 peer-reviewed journal articles over a 10-year period (2010–2021), depicts how complex the simplified structure in Figures 3 and 4 can be in practice. But, it does not change the finding that AM technologies have greater flexibility and agility than traditional SC.

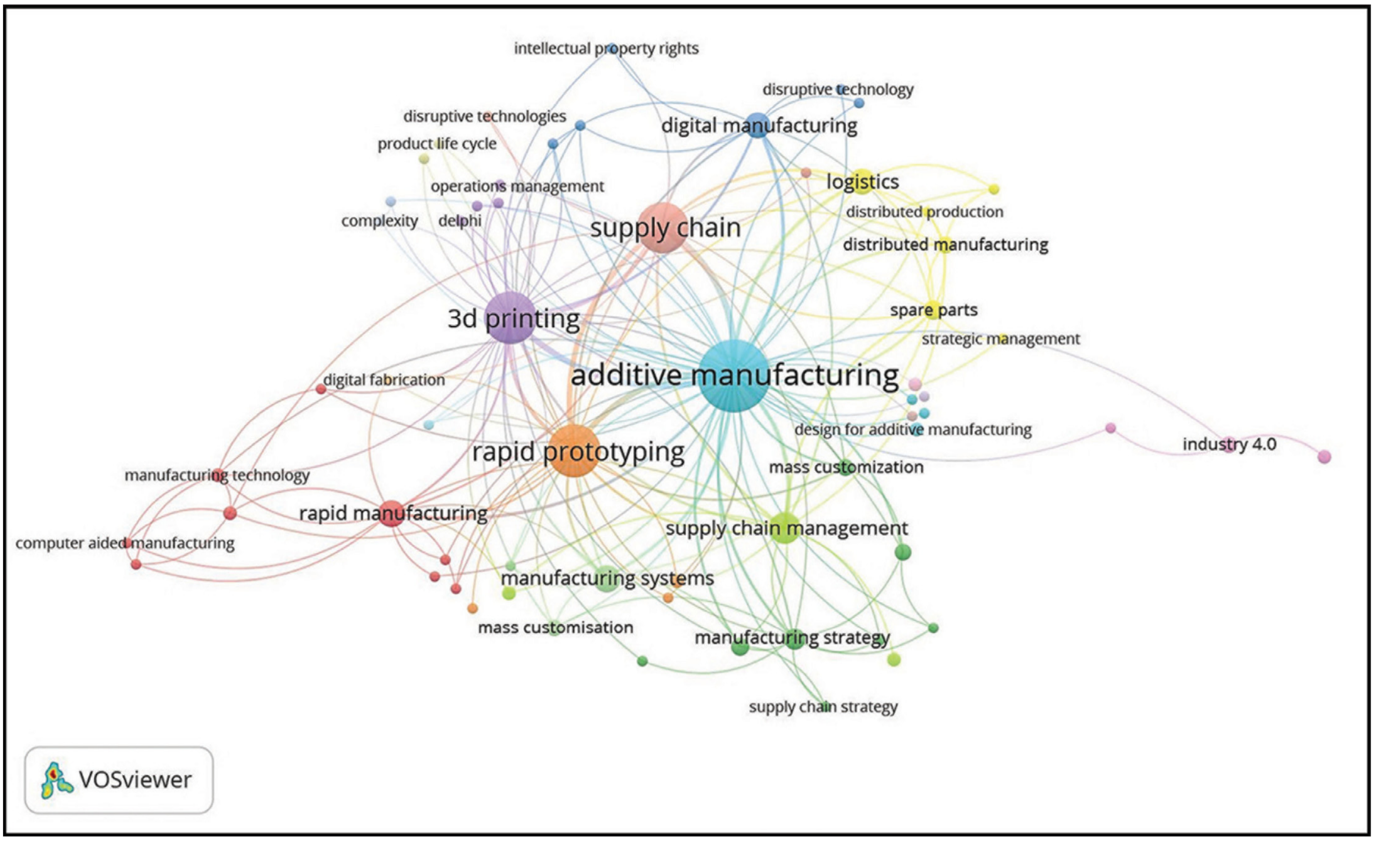

Figure 5. Integrating AM technology (brown), strategy (green), management (violet and blue) and supply networks (yellow) [88].

8. Conclusions

A series of globally influential events, including the COVID-19 pandemic, the war in Ukraine, the Evergreen accident in the Suez Canal, and the collapse of the Baltimore Bridge, in recent years has acted as a catalyst, bringing the need for alternative solutions to address SC disruptions, beyond traditional approaches, to the forefront. All these and similar crises, having some global effects, have made the costs of instability, uncertainty and stress more visible. The traditional structure of SCs has been observed to limit their ability to effectively manage disruptions caused by crises.

Therefore, the need for a new dynamic application, including AM technologies, has emerged as both a priority and necessity. Offering a number of material, administrative, technical and structural advantages over traditional SCs, AM technologies can be seen as potential solutions to overcome the challenges of traditional logistics support applications. AM technologies, having the capacity to eliminate administrative restrictions, political obstacles and technical barriers encountered at national borders, have the potential to cause significant transformations in logistics. However, at the point where current technology has reached, there appear to be some obstacles that prevent full implementation.

With the expectation that these challenges will be overcome soon, the process of transforming DCs into hubs and spokes centers with AM technologies has already begun, albeit slowly. This slow but inevitable shift in SC dynamics will facilitate centralized and customized production, and enable rapid fulfillment of spontaneous orders from customers worldwide. Additionally, beyond this, it may help to enable the formation of more resilient and sustainable SCs.

The application of AM technology is expected to significantly transform many industries in the near future. However, the extent of this transformation will depend on advancements in areas such as material science and AI integration. These developments may present challenges in scalability and sustainability, particularly within SCs. As these technologies evolve, AM will play a pivotal role in enhancing industrial efficiency and sustainability, ultimately becoming a cornerstone of future manufacturing applications.

As a conclusion, the reason for this is that the agile structure of AM-supported SCs, which have a more independent and fragmented structure than traditional SCs, exhibits greater resilience in facing and managing crises to cope with logistics disruptions.

9. Methodology

This study employs a qualitative, exploratory approach to analyze existing literature on logistics and AM, assessing the feasibility of AM techniques in mitigating the negative effects of SC disruptions amid growing competitive pressures. By examining the advantages and limitations of the most advanced AM technologies—encompassing diverse types and functions—alongside the technical, administrative, and structural requirements for their integration into modern SCs, this research provides an alternative to existing methods to prevent logistics support disruptions. Each article was assessed based on research design, sample size, data sources, and peer-review status. The literature review was conducted using keywords such as 'additive manufacturing', '3D printing', 'supply chain resilience', and 'sustainability'. Only peer-reviewed journal articles and conference papers, primarily published after 2020, were included. To ensure relevance to the manufacturing sector, studies focusing on non-industrial applications

Research Design: Using documentary analysis and case study methods, this study assesses the potential of AM techniques as a solution to SC disruptions. It examines the types, causes, and consequences of disruptions, supported by real-world cases from logistics support systems. By focusing on logistics challenges and key SC performance indicators, our research integrates insights from both field examples and existing literature to explore the potential role of AM in enhancing SC efficiency.

Data Collection: The data required for the initial phase of this academic study were obtained primarily from peer-reviewed articles published in journals specializing in logistics, supply chain management, and AM technologies, as well as from the events that happened, online databases, and official websites. The collected data were analyzed using thematic analysis to identify key challenges and recommendations. The primary focus areas included:

- Logistics and SC dynamics: examining the causes and consequences of disruptions in global SC management from a comprehensive perspective.
- AM technologies: evaluating advancements in AM technologies to identify opportunities for mitigating the negative impacts of logistics disruptions and highlighting areas of potential improvement.

Integrating AM to enable sustainable and resilient SCs: given that many disruptions occur unexpectedly and cannot be completely prevented despite current measures, the aim is to investigate whether AM technologies can increase both the resilience and sustainability of SCs. This study also addresses identifying strategies to reduce disruptions while promoting long-term efficiency and environmental sustainability.

Scope and Limitations: This study specifically examines the paradigm of logistics support process disruptions without employing primary data collection methods such as surveys or interviews. The analysis, supported by real-world case examples, is confined to a framework based solely on the increasingly prevalent use of AM technologies, rather than the broader range of tools available for mitigating SC disruptions. The interaction between AM technologies and SCs can be considered from two distinct perspectives: the first focuses on providing logistics support for the tools and infrastructure required by AM technologies, while the second examines the use of AM to enhance the efficiency of SC processes. This study is limited to the latter perspective.

Ethical Considerations: The research is based on publicly available data, adhering to ethical standards. All sources are properly attributed and cited.

Declarations: The authors did not receive support from any organization for the submitted work, and all of them contributed equally to the article while designing the conception, material preparation, data collection, and analysis. All authors read and approved of the final manuscript.

Author Contributions: Conceptualization, M.H.K., M.K., E.K. and M.M.F.; Methodology, M.K. and M.M.F.; Software, M.H.K., E.K., M.M.F. and M.Z.S.; Validation, M.K., E.K. and M.M.F.; Formal analysis, M.K., M.M.F. and M.Z.S.; Investigation, M.K., E.K., M.M.F. and M.Z.S.; Resources, M.H.K., M.K. and M.Z.S.; Data curation, M.H.K., M.K., E.K., M.M.F. and M.Z.S.; Writing—original draft, M.H.K., M.K., E.K., M.M.F. and M.Z.S.; Writing—review & editing, M.H.K., M.K., E.K., M.M.F. and M.Z.S.; Visualization, M.H.K.; Supervision, M.K., E.K., M.M.F. and M.Z.S.; Project administration, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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