

Impacts of Adopting Additive Manufacturing Process on Supply Chain: Systematic Literature Review

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Abstract: *Background:* The objective of this literature review is to systematically explore the supply chain (SC)-related issues of additive manufacturing (AM)-based production processes. For SC sustainability, efficiency, and performance improvements, the adoption of disruptive technologies like AM plays a vital role, because the product's SC benefits in terms of reduced total lead time and costs. *Methods:* To explore the state-of-the-art influences of AM on the SC in this study, 978 papers published in peer-reviewed journals from 2004 to 2023 were retrieved, and 70 of these were identified as the most relevant and then reviewed. *Results:* As an outcome, the results of this review paper indicated a lack of documented studies in developing countries and, as a result, limited research works, for instance, in fashion industries were observed. In addition, AM best practices in the SC context have been identified and categorized as cost-related, time-related, inventor-related, as well as energy-, waste-, and environment-related factors, SC efficiency factors, and flexibility, marketing, and manufacturing-related factors. *Conclusions:* By identifying these categories, the study aims to contribute to the efforts of transforming traditional manufacturing into AM-based processes, for which a framework for the AM SC implementation is developed. In summary, the systematic review indicated that further research work is needed on the impacts of the identified AM best practices on SC performance.

Keywords: additive manufacturing; best practices; disruptive technologies; supply chain; supply chain management; sustainability



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1. Introduction

The concept of sustainability has historical roots in the seventeenth century [1] and rose to prominence thanks to the *Brundtland Report* of 1987 and the work of the World Commission on Environment and Development (WCED). According to Clark [2], there is a notion that human beings have a responsibility to protect the environment and future generations. Additionally, the sustainability concept focuses on three triple bottom line (TBL) principles, i.e., (1) economic, (2) environmental, and (3) societal equality [3]. Economic sustainability is a concept that focuses on maximizing the financial gains of business operations for both internal and external stakeholders. The emphasis is on financial matters, and quantitative indicators are used throughout. Cost is a crucial measure of economic sustainability, as reported by Aguado et al. [4], and it comprises costs for materials (inventory), equipment, energy, and transportation, as well as process and operation efficiency [5]. The second TBL principle, i.e., environmental sustainability, focuses on analyzing and implementing organizational efforts to reduce the effects of waste release, resource usage, and energy consumption. Some examples of environmental indicators include materials [6], energy, emissions, wastes [7], resource consumption, and efficiency [8].

On the contrary, the societal sustainability dimension is concerned with analyzing and placing organizational actions into practice to maximize the well-being of internal

and external stakeholders. Additionally, it concentrates on concerns pertaining to the working conditions of employees, their health, satisfaction, and their safety [9]. Thus, nowadays, addressing the three TBL dimensions results in the accomplishment of SC sustainability goals [10]. Vargas et al. [11] claimed that a sustainable SC will be able to enhance management performance and value while minimizing unfavorable effects. In the same way, implementing sustainability in a SC will cut down the time and costs related to environmental degradation, enhance brand identity, foster a socially responsible image, and benefit businesses [12]. In addition, SC sustainability encompasses all activities that reduce carbon footprints and improve ecological, environmental, and social conditions [13–15].

However, according to Krishnamoorti et al. [16], industries practicing the traditional manufacturing (TM) supply chain are having difficulties in achieving and maintaining the three sustainability aspects, i.e., economic, environmental, and societal. This system also has more difficulties when it comes to reducing environmental issues like greenhouse gas emissions, increasing energy efficiency, and reducing waste and pollution [17]. Additionally, Sala et al. [18] claimed that one of the main difficulties now facing traditional manufacturing businesses using standard SC systems is lowering prices, lessening their environmental effect, and boosting productivity and efficiency. They also had difficulties ensuring that their workers had respectable jobs and social protection, as well as promoting economic progress across society [19].

Similarly, according to Reeves [20], to produce and deliver finished products to end users, the TM supply chain system requires raw material suppliers, component and original equipment manufacturers, wholesalers/retailers, logistic service providers, etc. Between these SC participants, there are forward and backward flows of materials, information, and funds, making traditional SCs more complex. As a result, it affects competitiveness and profitability, as well as the fulfilling of customer satisfaction and needs, providing quality products to the market, and manufacturing on-demand and customized products. Complexity has many demerits on the SC; among others, it leads to high operational costs, customer dissatisfaction, a delay in delivery times, excess inventory, or inventory shortages (stock-outs), and a lack of cooperation, collaboration, and integration among SC players, etc., [21] which make the whole SC process unsustainable. Due to the unsustainability of the SC in the global economy, society and the environment are affected [22]. All the above cases indicate the significant problems of the TM supply chain in economic, societal, and environmental dimensions. Therefore, it is vital and imperative to adopt sustainability in the SC to corroborate the different prospects for sustainable performance of the firm.

In this regard, the adaptation of disruptive technologies like AM alleviates those types of problems by shrinking the SC and making the supply chain more sustainable [23], and it has the potential to revolutionize and alleviate SC sustainability-related problems [24]. Through the implementation of AM technology, a significant improvement in SC efficiency and performance was obtained with a significant contribution to the sustainability of the process in terms of impacts on the economic sustainability dimension by reducing costs and time, replacing physical inventory holdings with digital inventory, thus resulting in less stock, material handling, and packaging [25]. In addition, AM is more competitive than TM from a SC financial (cost) perspective, including the cost of production, transportation, warehousing, and service [26]. Regarding the environmental dimensions of sustainability, as compared to TM, AM reduces primary energy and greenhouse gas emissions (CO₂ emission) [27], and from a societal sustainability dimension, since the production of goods in AM takes place close to the customer, wholesaler, and retailer, this would change the conventional flow of goods, reducing upstream transportation to basic materials and downstream transportation to locally produced finished goods [28]. This reduces the number of customers served [29]. It simplifies and makes the SC sustainable and increases efficiency and responsiveness for demand fulfillment [30].

In this topic area, for the past decade, different review studies have been conducted to illustrate the impacts of AM in a SC context. However, the existing review studies have their own limitations and gaps. For example, the review study by Asma et al. [31]

considered only the economic benefits of AM and missed the impacts of AM on the SC in terms of environmental and societal sustainability dimensions. The paper reported by Vojislav et al. [32] aimed to review AM technologies and their state-of-the-art applications in tooling, biomedicine, and lightweight structures for the automotive and aerospace sectors. Their review resulted in illustrating the benefits of AM in material saving and product customization in many industrial sectors. This same paper also missed the environmental sustainability dimension. Similarly, the review study reported by Huang et al. [33] focused only on the societal impacts of AM from a technical perspective. In addition, the systematic review paper in [34] illustrated and discussed the application of AM in different areas of the SC by using the SCOR framework. Even if the implementation of AM has an important effect on the consumer perspective (downstream supply chain) [35], the study in this review paper missed the consumer perspective (societal dimension). Moreover, the systematic literature review in [36] demonstrated the impacts of AM on the SC of the aircraft spare parts industry by considering both centralized and decentralized structures of AM SCs; this paper focused only on the interconnection of the industry findings on the SC of the aviation spare parts. In addition, all the mentioned reviewed papers lack a description of the most significant (in ranking) applications or best practices of AM in a SC context. This indicates that no studies were conducted using the three TBL dimensions (economic, environmental, and societal) to investigate the effects of AM best practices on SC sustainability, thus indicating that there is no general framework that includes the three TBL sustainability dimensions to illustrate the best practices of AM on SCs. Thus, the novelties of the study reported in this article are as follows: (1) We reviewed recently published works from 2004 to July 2023; (2) we considered the three sustainability principles to identify the best practices of AM from a SC perspective, such as economic, societal and environmental contexts; (3) we qualitatively prioritized and ranked the identified AM best practices for SCs; and (4) we developed a conceptual framework to qualitatively study the strengths and relationships between AM best practices on SC sustainability.

With the above background in mind, this current study seeks to examine the potential impacts of AM in SCs by considering the three TBL dimensions. Hence, to meet the objectives, the remaining parts of this study are organized and outlined as follows: Section 2 presents the materials and method of the literature review. Section 3 presents some related studies, including the economic, environmental, and societal impacts of AM from SC perspectives. Then, the findings of the bibliometric data analyses, together with the main findings and results of the study, are reported in Section 4, followed by a discussion on the major findings and results of the study and outlooks on some future research in Section 5. At the end, the drawn conclusions are given in Section 6.

2. Materials and Methods

To identify the economic, environmental, and societal impacts of (best practices of) AM from a SC perspective, a review of the literature was conducted systematically. The steps used to review the literature are outlined and illustrated in Figure 1 below.

2.1. Literature Survey

To search for the published studies, to recover as many documents as possible, and to ensure the most comprehensive coverage, publications that appeared in renowned databases like Elsevier (Amsterdam, The Netherlands), Taylor and Francis (Abingdon, UK), Emerald (Leeds, UK), IEEE (New York, NY, USA), Wiley (Hoboken, NJ, USA), Springer (New York, NY, USA), ASME (New York, NY, USA), MDPI (Basel, Switzerland), Springer, Sage (Thousand Oaks, MA, USA), and NIST (Gaithersburg, MD, USA) were used. To retrieve conference papers, journal articles, literature reviews, and book chapters from these data bases or publishers, keywords “additive manufacturing”, “3D printing”, “rapid prototyping and/or manufacturing”, “additive manufacturing and supply chain”, “3D printing and supply chain”, and “Rapid manufacturing and supply chain” were used. These keywords were used to find and include all relevant articles covering AM and SCs.

Through searching the data bases, 978 papers were retrieved that focused on AM and SC-related factors and were further screened, as illustrated in Figure 1.

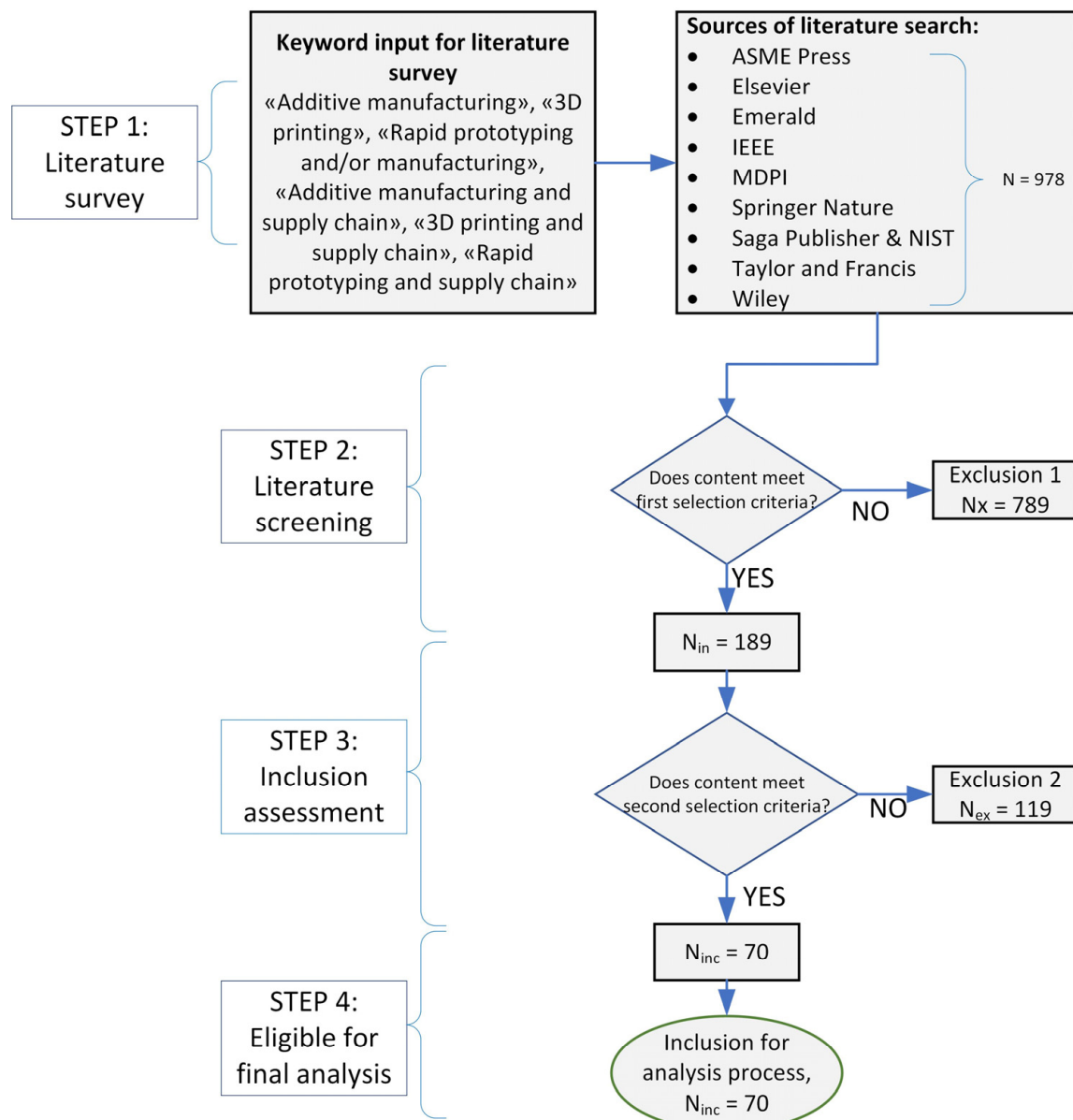


Figure 1. Overview of the literature review procedure.

2.2. Literature Screening

From the identified 978 studies, screening was conducted by reading the titles, abstracts, keywords, objectives, and conclusions of these papers. The screening process was conducted by using the selection criteria, such as:

A focus of the study areas: as per the scope of this paper, the identified studies must focus on the economic, environmental, and societal sustainability dimensions. Additionally, they must focus on the impacts of AM within SC perspectives.

A consideration of time frame and language limitations: Papers published in the last twenty years (between 2004 to 2023, with few exceptions), academic articles published in English, and those focusing only on supply chain-related factors and matching the objective of this study were considered as candidates for further review.

Then, based on these selection criteria in the first selection stage, 189 papers were identified. Upon full-text reading, 119 papers were then excluded, and 70 studies were

selected that fulfilled the objective of the study and were thus entered into an Excel spread sheet for further analysis.

2.3. Data Analysis

After a systematic identification of the relevant papers, country of origin and continent, year of publication, publisher, journal name, and focus areas of the existing studies (by types of industry), their findings were considered and analyzed. Then, economic, environmental, and societal best practices of AM in the SC context were identified. Then, the identified best practices were classified into six factors. To summarize the results or outcomes of these papers, pie charts, histograms, and tables were used. Finally, the findings, results, and conclusions were drawn, gaps were identified, a conceptual framework was developed, and future research directions were proposed.

3. Supply Chain in Additive Manufacturing Production Process

In this section, a review of the related studies on SC perspectives of AM and its best practices are explored.

3.1. Time, Cost, Inventory, and Operations Efficiency-Related Factors

The purpose of the study reported in [37] was to optimize the SC configuration of a personalized product under various demand uncertainties by developing a design for additive manufacturing (DfAM) and a design for a supply chain (DfSC). Based on the simulation results, the SC setup was examined during the product design stage. The outcome of their studies illustrated the benefits of AM in improving SC efficiency in terms of lead time and overall costs. Levin et al. [38] modeled both the additive and TM systems to compare their SC efficiency. The results of their study illustrated that AM provides a good improvement in a SC's performance. To conduct their study, two different SC networks, i.e., (1) a traditional approach and (2) an approach that adopts AM for the healthcare industry, were considered. Their results showed the tangible advantages of a 3D-printing supply chain network (SCN) over a traditional counterpart, including a reduction in lead time and costs. Fabrication of final products using AM has economic advantages not only because it reduces the lead time and production costs [39] but also because AM reduces delivery and supplier lead times, reduces the setup and changeover times for new product development and production, as well as reducing the number of assemblies [40]. The study in [41] looked at how AM affected the management of spare part inventories. Their research demonstrated that a decrease in holding costs (which has benefits related to inventory) has a greater influence on lowering the stock-out. The research by Mohsen [42] studied the effects of AM on the SC and investigated its potential for change. Additionally, they found that lead times for AM were shortened, and new designs used less time to reach the market. Studies reported in [43] also indicated that AM reduces the number of factory workers in low-wage countries to produce small lot sizes, and the firms become profitable in small market segments and reduce finished goods inventory.

The proposed study by Barz et al. [44] examined the outcomes of integrating AM in the healthcare business SC from a logistical perspective. Through available resources and real-time observations, simulation models of both traditional SCs and AM-integrated SCs of healthcare were developed by the authors. Their findings demonstrated the advantages of this technology in decreasing lead times. The study in [45] attempted to investigate the effects of AM as an innovative technology in logistics and SCs. The identified effects of AM on SCs and logistics from the literature review were classified into seven crucial issues: (1) SC cost reduction; (2) more adaptable inventory and logistics management; (3) widely adopted and accepted mass customization; (4) manufacturing decentralization; (5) quick prototyping and increased design flexibility; and (6) resource efficiency and sustainability are improved.

Milad et al. [46] developed a cost model and evaluated the economic feasibility of AM for slow-moving vehicle component SCs by taking the costs of the TM spare part SCs with

centralized and outsourced AM spare part SCs. They analyzed and compared the SC costs of 14 different spare parts as well as the overall spare part SC cost that was produced by both TM and AM. Their results illustrated that among the fourteen components, three of them indicated cost reductions that were produced with AM rather than TM. From the total SC cost perspective, AM polymer components showed more potential than metal to replace the TM approach. In addition, this study illustrated the competitiveness of AM from a financial (cost) perspective, including the cost of production, transport, warehousing, and service. This can be attributed to the fabrication of complex components with the AM process, which needs only raw materials and 3D CAD files. As a result, the number of assemblies was minimized; it cut down the setup and changeover time and enhanced SC just-in-time production [46].

The adoption of AM technology significantly improves SC dynamics, lowers shipping costs, and shortens delivery lead times; thus, parts can be produced on demand, and this reduces the need for stocking safety inventory [47]. Jan et al. [47] obtained these findings by conducting a case study based on data obtained in the literature to evaluate the effects of AM in the aviation spare part SC by considering three SC situations, namely: (1) traditional SCs, (2) centralized AM SCs and (3) distributed AM SCs. The study by researchers in [48] provided a general representation of a detailed SC configuration or a detailed system-level cost analysis for AM biomedical implants and developed a comprehensive AM SC model. The developed model includes the production of implants, post-processing, and transportation. Their results indicated that biomedical implants fabricated through AM have lowered the inventory level and delivery expenses. With localized SC configurations, the delivery time was reduced, and the distances between the SC network nodes expanded when AM technology or machines were used [49].

The application and state-of-the-art AM technology on biomedicine, tooling, and lightweight components for the vehicles and aviation sectors were reviewed in [50]. And their reviewed results illustrated the increase in supply chain dynamics by reducing the “time-to-market”. In their study, Bram et al. [51] showed the advantages of a shorter AM lead time in lowering or reducing after-sale logistic costs. According to the work of Christian et al. [52], home fabrication, reduction in inventory, and increased decentralized manufacturing were some of the benefits of AM in impacting SCs.

The paper by Desiree et al. [53] assessed the possible futurity of 3D printing in relation to socio-technical systems, consumption, and production, where their results illustrated that SCs are expected to become less transport intensive. Ming and Yi [54] have also considered the adoption of online and in-store retail 3D-printing environments to assess and evaluate their effects on company product-offering pricing and inventory choice. Their case study indicated that when 3D printing is used in stores, the company achieved structural effects due to the changes in the SC structure and achieved postponement benefits in inventory management. In addition, cost-sharing agreements can coordinate the SC where 3D printing is utilized in-store and where the supplier manages the inventory of raw materials. The researchers in [55] introduced the tools necessary for dynamic supplier selection that considers both cost and delivery performances. This paper concluded that outsourcing the SC spare part to multiple AM suppliers indicated profitable results by means of cost-cutting, shortening lead times, and supporting cost and time tradeoffs. In addition, their results indicated that it enables professionals to outsource troublesome components that could otherwise have been manufactured in-house due to rising minimum order quantities, higher inventory prices, and lengthy lead times.

The structure of the SC will be impacted by AM technology that can improve production process efficiency and replace subtractive technologies [56]. Source, production, and customer nodes of a two-stage supply network were used by Marta et al. [56] to quantify the effects of AM on the SC structure. For this purpose, four measuring factors (indicators) like (a) the total cost, (b) tone-kilometer per client (on the second stage, i.e., from a production site to a customer site), (c) number of active production facilities, and (d) transportation costs in the first and second stages were compared. Their computational

results indicated that all indicators are improved (reduced) through the adoption of AM technology. The empirical study by Siavash et al. [57] focused on studying the effect of using 3D-printing technology on building SCs and they aimed to contribute insight into how potentially disruptive technologies impact the eco-performance of the entire SC. Their main findings have also illustrated that 3D-printing technologies provide several advancements in manufacturing efficiency, such as shorter lead times, integration of function parts, facilitating the ability to minimize material usage, and reducing logistical and production efforts. Yao et al. [58] investigated the impacts of AM on supply chain management (SCM) by separately implementing two balanced SCs using a lot-sizing comparison between AM and SM. They developed a joint economic lot-sizing mode to comparatively analyze the total cost (including inventory, transportation, and production costs) of each system. The comparative results of their study indicated that AM could alleviate the service SC by lowering the batch size, minimizing inventory holding factors, and reducing the costs associated with obsolete products.

The study by Sabarish et al. [59] aimed to assess and evaluate the potential methods to introduce AM into the spare part SC. They developed a conceptual design for deploying rapid prototyping technology in the spare part SC that can reduce inventory. Daniel et al. [60] have also developed system dynamics modeling to illustrate how the behavior of a SC looks when a disruptive technology such as AM is implemented. Their model was shown by two feedback cycles, namely, a causal diagram that has thirteen variables related to the SC and a data flow diagram of the three essential links of the SC, as well as order display traceability (network of supplier, manufacturer, and distribution).

The results of their analysis indicated a production time reduction for products that have greater complexity, detail, and inventory levels due to the best practices of AM in storing and production.

AM is a promising technology in the fourth industrial revolution (Industry 4.0) that can improve SC efficiency, competitiveness, and adaptability. In addition, it makes it easy for the development of distributed SCs, which can result in improved product availability, inventory levels, and lead times [61]. Firms are expected to decrease cost performance metrics and increase responsiveness to the current competitive SC challenges. For instance, Philip et al. [62] examined the contribution of AM towards e-commerce SC network durability, competitiveness, and profitability. They established a utilization policy for AM in the SC network for the companies to continuously improve their performance metrics related to the total network cost and response time. Their results illustrated that utilizing AM in such a network can prove such metrics beneficial and significantly improve network performance metrics (reduce the total network costs and response times). Similarly, the study by Banu et al. [63] examined the contribution of AM e-commerce SC network resilience and competitiveness. Their results confirmed that the adaptation of AM greatly contributes to network cost reductions and responsiveness performance improvements. According to the study reported by Sudipta et al. [64], 3DP possesses several types of pros as compared to TM, which include accelerating the design process, minimizing production times, and reducing the costs related to inventory, warehousing, packaging, and logistics.

Li et al. [65] examined the drawbacks of modular design and the effectiveness of AM in providing a high variety to meet customer demands. A case study was conducted by using in-depth interviews with experts and design-change data. Their findings indicated that AM could act as a SC solution, managing complexity and allowing products and SCs to absorb contextual variety efficiently and effectively. Manufacturing and delivering products to customers required the integration or complexity of different players, such as components and raw material suppliers, original equipment manufacturers and distributors, retailers, and logistics service providers, to form manufacturing SCs. By implementing AM, procurement costs that have a linkage with complex products and integrating different parts in one component can be improved [66]. Due to the use of AM technology, large industries are becoming smaller, and lengthy SCs are becoming shorter [67]. A lot of activities are streamlined by combining designs, consulting, sales, and production in one location and

converting the warehouse into a small lab. The research by Evgeni et al. [68] discovered that the main cost components, such as manufacturing costs and the details of (related) SC costs, are greatly reduced when TM is replaced with AM technology. This allowed for more flexible and efficient product design. The study in [69] claimed that firm SCs, disrupted through AM production throughput and cost reductions, caused businesses to develop faster design, development, and manufacturing cycles. Utilizing AM technology decreased the amount of buffer stock needed to handle supply risk and demand spikes, which enhanced inventory performance [70]. It also reduced the number of spare parts carried that were at risk of becoming obsolete. The case study by Thembani et al. [71] showed how the addition of AM parts improved the spare parts inventory replenishment lead times. Martin et al. [72] claimed a saving of production costs from 36 to 46% by implementing AM, and operating costs were also decreased. The study by Suzanne et al. [73] demonstrated a lead-time reduction through quick production techniques like AM and a fast and flexible capability to customize products.

Furthermore, Abhijeet et al. [74] used the SD simulation method to investigate the impact of AM implementation on aircraft SC networks, where their study results illustrated a significant improvement in SC efficiency, balanced inventory levels, and increased responsiveness. In addition, according to Tuck et al. [75], the adoption of AM resulted in a reduction in material distribution and inventory holdings for work in progress, and nonvalue-added activities like material movement were minimized. Since this technology requires only 3D data files and raw materials to produce complex parts layer-upon-layer, it improves the entire SC from the perspective of the cost of assembly to distribution and transportation [76], as well as reduces the cost of new products being introduced to the system [77], and the cost of distribution [78].

3.2. Resource, Energy, Pollution, and Waste-Related Factors

The reviewed papers illustrated the benefits of AM in environmental and societal sustainability aspects. Fabrication of complex components with the AM process eliminates waste and waste generation [21,23], reduces raw material consumption [35], responds to customer demands [25], leads to simultaneous improvements in customer service [21,24], and has clear safety requirements, stated legal requirements [22], and mass customization [52]. AM moves production sites closer to the customer [31] and reduces disruptions and carbon emissions in the supply networks [74]. By lowering the product weight, transportation, and material waste, as well as enhancing functionality, the application of AM has a favorable environmental impact [79]. Additionally, according to the work reported by Karel et al. [80], AM technologies enabled the production of complicated work items in near-net shapes, opening up the potential for manufacturing with little waste and sustainability. The study by Zhen [81] used the system dynamic approach to create an international SC model, and the results showed that employing 3D printing will greatly minimize the amount of transportation and bring industrial activities closer together. According to Evgenii et al. [68], AM can decrease the number of raw materials used in the SC and eliminate the need for energy-intensive, inefficient, and environmentally damaging manufacturing methods. The study by Inigo et al. [69] implied that AM technologies introduce new opportunities to change a product's architecture at any stage of product development while compressing the SC and enabling quick responses to changing customer demands. To significantly lower SC costs, AM technologies have the potential to do away with the need for both low-level assembly employees and high-volume manufacturing facilities [82]. Filipe et al. [83] used a descriptive sustainability evaluation to qualitatively identify and evaluate AM implications on sustainability, the environment, and society dimensions, to undertake a thorough assessment of the technology from a global sustainability viewpoint. Furthermore, a top-down model was applied to quantify the changes in energy and CO₂ emissions. Their findings identified that 3D printing effectively reduced costs, production input (raw material), and output in markets with high value, low volume, and customized production chains, such as the manufacturing of aviation and medical components. The

results of their model showed that 3D printing reduced total primary energy supply and CO₂ emissions.

To support and help capture SCM emerging business opportunities that can come from AM, Peng et al. [84] developed a decision support model in which logistics concern problems in the aviation sectors of the spare parts business were considered, and their findings indicated the benefits of AM in producing on-demand products without the requirements of a new setup and tooling and its benefits towards the basis for new solutions in SCM. Malte et al. [85] used interviews and utilized publicly available information in three case sectors to analyze and compare supply chain costs (SCCs) before and after the implementation of AM. Their finding confirmed the simplification of SCCs (in terms of the number of products, processes, suppliers, and marketers) in one of the sectors after switching to AM, which, however, led to some complications in another sector. In addition, in the third sector, their results illustrated that the impact of switching to AM on SCCs was dependent on several variables. As a result, they concluded that the adaptation of AM is not a silver bullet to simplify SCs in every complexity. According to Malte et al. [85], participating or inviting customers at the stages of process and product design will play a significant role in changing the procurement processes. In addition, it will reduce the complexity of products, supply risks within the SC decreases, products can be produced at the location of use, and it will reduce the number of suppliers involved. The research paper reported by Vojislav [86] illustrated the significant impacts of AM on SC dynamics; they tried to investigate its impact on spare part SCs. To meet their objectives, three SC scenarios were investigated, namely (1) a conventional SC, (2) a centralized AM-based SC, and (3) a distributed AM-based SC. Their findings showed the spare part SC that used AM is more sustainable than the subtractive one.

Within the digital manufacturing era, Thomas [87] studied and explored how the configuration opportunities of SCs are impacted by AM. This study first described the efforts of the current research and then proposed an integrated decision-making process and framework for the design and management of SCs and for future SC reconfiguration opportunities arising from the adoption of AM on a supply network. Their study results indicated improvements in SC configuration and sustainability performance as compared to the subtractive networks raised from the effects of AM technology. Implementation of AM could completely pursue new approaches in terms of product development, design, and product properties, and this leads to customer individualization of the products in SCM that can be used to react quickly and flexibly to customer requests, and it simplifies market entry [88]. Through Industry 4.0, like AM technology firms, the SC can respond quickly to unexpected events and causes due to disruption [89].

In one of the oldest and most prestigious global fashion footwear industries, change was necessitated due to the shortcomings of the TM techniques, the worldwide consumer trends, as well as competitive agility [90]. This paper conducted an in-depth study of the implementation and usage of 3D printing in Mexico's fashion footwear sectors by employing a mixed-method approach by including manufacturers and suppliers. The study shared 3D-printing adoption of local behavior and global best practices, and they discussed the state-of-the-art of this technology in the fashion industries. Their in-depth analysis indicated that the implementation of 3D printing in the global footwear industry had disrupted stakeholder dynamics in an early traditional industry and revolutionized the process of creating shoes across the whole value chain. In the areas of production and management, related factors that change over to AM have an impact on internal processes, management activities, SCM processes, and components relating to the supply and demand-side of a firm's SC, reducing the amount of sub-production required and improving the supplier connection within the network [91]. AM adoption positively influenced SC performance and, as a result, firm performance [92], as well as simplifying SCs for a number of products, processes, suppliers, and marketers [93]. One of the studies by Fares et al. [94], which was conducted in aeronautic sectors, illustrated the benefits of AM in terms of cost and environmental impacts. AM technology offers a potential

reduction in raw material consumption and production waste [95]. As a summary, based on the above literature review, the key best practices of AM impacts in the SC context are summarized and included in Table 1.

Table 1. Summary of additive manufacturing best practices on SCs.

Findings and Results	Author (Year)
Cost-Related Factors	
Reduced shipping costs (i.e., transport) and after-sale logistic costs.	Sala et al. (2015) [5], Hahn et al. (2015) [23], Khoo et al. (2015) [24], Asma et al. (2020) [31], Huang et al. (2013) [33], Jan et al. (2022) [37], Bram et al. (2018) [51]
Reduced total costs.	Rajak and Vinodh (2015) [9], Rydzik and Kissoon (2022) [19], Zeplin et al. (2021) [30], Asma et al. (2020) [31],
Reduced costs of distribution, assembly, and carry.	Azzone et al. (1996) [6], Asma et al. (2020) [31]
Reduced costs of production or manufacturing.	Hahn et al. (2015) [23], Asma et al. (2020) [31], Huang et al. (2013) [33], Guido et al. (2018) [39], Evgenii et al. (2019) [68], Martin et al. (2017) [72]
Reduced costs of warehousing (decrease holding costs).	Mojtaba and Fabio (2016) [23], Asma et al. (2020) [31], Jan et al. (2022) [37], Sirichakwal and Conner (2016) [41]
Reduced cost of service.	Hahn et al. (2015) [23], Asma et al. (2020) [31]
Low costs of new product introduction into the system.	Teece et al. (1997) [7], Asma et al. (2020) [31]
Reduced life-cycle costs, reducing supply chain costs.	Sachin and Rajesh (2020) [15], Bogers et al. (2016) [26], Asma et al. (2020) [31], Banu et al. (2023) [63], Janssen et al. (2014) [82]
Reduced delivery costs.	Massimiliano et al. (2007) [25], Asma et al. (2020) [31]
Supported tradeoffs in costs.	Zeplin et al. (2021) [30]
Reduced inventory costs.	Asma et al. (2020) [31], Huang et al. (2013) [33], Jan et al. (2022) [37]
Reduced procurement costs.	Asma et al. (2020) [31], Barz et al. (2016) [44],
Reduced packaging costs.	Jan et al. (2022) [37], Asma et al., 2020) [31]
Reduced raw material costs.	Dahmus (2014) [8], Asma et al. (2020) [31]
Reduced tone-kilometer per customer (carbon emission costs).	Asma et al. (2020) [31]
Time-Related Factors	
Lead-time reduction (shortening of lead times).New designs will take less time to reach the market.	Sala et al. (2015) [5], Dahmus (2014) [8], Rajak and Vinodh (2016) [9], Mitchell and Walinga (2017) [10], Filiz (2011) [21], Zeplin et al. (2021) [30], Vojislav et al. (2011) [32], Binoy et al. (2020) [36], Bram et al. (2018) [51], Guido et al. (2018) [39], Attaran. (2017) [76], Themban et al. (2019) [71], Suzanne et al. (2004) [73]
Reduced delivery lead times.	Bai et al. (2019) [12], Khoo et al. (2015) [24], Victor et al. (2021) [49], Melanie and Abubaker (2017) [70]
Eliminated supplier lead times.	Bai et al. (2019) [12]
Reduced setup times (supporting tradeoffs in lead times).	Aguado et al. (2013) [4], Zeplin et al. (2021) [30]
Reduced changeover times.	Aguado et al. (2013) [4], Teece et al. (1997) [7]

Table 1. Cont.

Findings and Results	Author (Year)
Time-Related Factors	
Reduced downtime.	Dahmus (2014) [8]
Reduction in time in production for complex parts (less production time).	Jan et al. (2022) [37]
Increases in supply chain dynamics by reducing the “time-to-market.	Peter (2015) [27]
Inventory-Related Factors	
Reduced safety stock inventory, decreased inventory holding concerns (reductions in inventories), lowered the stock-out, and reduced finished goods inventory.	Almi and Boumar (2023) [1], Aguado et al. (2013) [4], Khoo et al. (2015) [24], Huang et al. (2013) [33], Maximilian and Gerald (2019) [34], Halassi et al. (2019) [35], Sirichakwal and Conner (2016) [41], Berman (2012) [43], Christian et al. (2017) [52]
Results in a reduction of material distributions.	Aguado et al. (2013) [4]
Implemented a build-to-order strategy (produced when order is confirmed).	Aguado et al. (2013) [4]
Reduced the inventory level or balancing inventory levels.	Almi and Boumar (2023) [1], Clark (2007) [2], Aguado et al. (2013) [4], Massimiliano et al. (2007) [25], Halassi et al. (201) [35], Binoy et al. (2020) [36]
Achieved postponement benefits in inventory management; more flexible logistics and inventory management.	Hahn et al. (2015) [22], Joao et al. (2019) [29]
Reduced nonvalue-added activities, such as material movement.	Aguado et al. (2013) [4]
Made SC less transport intensive, reduced the flow of goods between customer, wholesaler, and retailer, reduced supplier transportation of basic materials, reduced downstream transportation for locally produced finished goods (this reduces up and downstream transportation), and reduced transportation.	Vargas et al. (2018) [11], Frederic et al. (2015) [28], Daniel et al. (2020) [60]
Energy- and Waste-Related Factors	
Reduced life-cycle primary energy consumption, reducing product weight, the volume of transportation, and the need for energy-intensiveness.	Dahmus (2014) [8], Bogers et al. (2016) [26], Daniel et al. (2020) [60], Evgenii et al. (2019) [68], Zhen (2016) [81]
Reduced greenhouse gas and CO ₂ emissions.	Dahmus (2014) [8], Bogers et al. (2016) [26]
Decreasing disruptions.	Dahmus (2014) [8]
Reduced wastes, material usage, and losses, reduced the amount of raw material required in the SC, and reduced polluting manufacturing processes.	Aguado et al. (2013) [4], Filiz (2011) [21], Vojislav et al. (2011) [32], Daniel et al. (2020) [60], Evgenii et al. (2019) [68], Karel et al. (2017) [80]
SC Efficiency and Firm Performance Factors	
Improved internal processes by eliminating the creation of new production lines for new product development, improving management activities (planning, organizing, leading, and controlling), reducing the amount of sub-production required and supply and demand-side of SCM components and processes.	Men et al. (2023) [14]
Improved SC efficiency (obtaining products at the right time, place, and the lowest cost, using resources efficiently); improved the efficiency of manufacturing lean just-in-time SCs; increased the efficiency of the production process and changed the structure of SC; supply chains become shortened, compressing the SC.	Aguado et al. (2013) [4], Islam, et al. (2021) [13], Asma et al. (2020) [31], Avner and Enno (2017) [67], Inigo et al. (2016) [69]
Significant impact on SC configuration and sustainability performance: SC can respond quickly to unexpected events and causes due to disruption.	Peter et al. (2015) [27], Mohsen (2017) [42]
Allow products and SC to efficiently and effectively absorb contextual variety.	Rydzik and Kissoon (2022) [19]

Table 1. Cont.

Findings and Results	Author (Year)
SC Efficiency and Firm Performance Factors	
Has positive influences on SC performance and, as a result, firm performance (improve SC and firm performances).	Sachin and Rajesh (2022) [15], Reeves (2008) [20]
Marketing and Manufacturing-Related Factors (Decentralized Manufacturing)	
Increase responsiveness for demand fulfillment.	Sala et al. (2015) [5], Shen et al. (2020) [17], Hahn et al. (2015) [22], Asma et al. (2020) [31], Christian et al. (2017) [52], Avner and Enno (2017) [67], Zhen (2016) [81]
Better spreading and popularization of mass customization; decentralization of manufacturing (manufacture products near the customers); facilitate rapid prototyping and design freedom; increase resource efficiency and sustainability; have clearly defined legal and safety aspects, move production site closer to the customer. Bring manufacturing operations closer together as the world becomes more localized and massive industries become smaller (societal sustainability).	Aguado et al. (2013) [4]
Results in a lean supply chain with low costs; improves agile SC.	Teece (1997) [7], Massimiliano et al. (2007) [25], Mitchell and Walingam (2017) [10]
Rapid response to fluctuating demands and provides customized products, quick response to customer demand, and the provision of customized solutions to meet unanticipated operational demands.	Dahmus (2014) [8]
Optimized designs, improved machine throughput, and reduced machine vacancy.	Khoo et al. (2015) [24], Guido et al. (2018) [39]
Parts are produced on demand without the need for tooling and setup (reduces the need for tooling and setup).	Teece (1997) [7], Inigo et al. (2016) [69], Suzanne, et al. (2004) [73], Klaus et al. (2020) [88]
Flexibility against key market disruption; volume, mix, delivery, and new product introduction flexibility; sudden disruption flexibility scenarios, such as demand uncertainty, demand variability, lead-time compression, and product variety. Fast and flexible capacity to customize products, and react quickly and flexibly to customer requests and changing customer demands; it simplifies market entry and leads to customer individualization of the products.	Avner and Enno (2017) [67], Evgenii et al. (2019) [68], Inigo et al. (2016) [69], Suzanne et al. (2004) [73], Karel et al. (2017) [80]
Create development and manufacturing cycles. Enable and create more efficient, flexible, and fast product designs, and reduce the number of procedures (starting from design to warehousing). Allow near-net shape manufacturing of complex workpieces (economic sustainability) and allow quick manufacturing methods.	Sala et al. (2015) [5], Shen et al. (2020) [17], Hahn et al. (2015) [22], Asma et al. (2020) [31], Christian et al. (2017) [52], Avner and Enno (2017) [67], Zhen (2016) [81]

3.3. Triple Bottom Line

According to Cagno [96], economic, environmental, and social factors are included in the TBL, which serves as the foundation for sustainability issues. The aim of economic sustainability for organizations is to minimize costs for both internal and external stakeholders. These sustainability dimensions target the financial aspect and stick to quantitative indicators. Cost is a significant indicator utilized by several authors [96]; this includes material, equipment, and other costs, as well as a return on investment, cost management, and operation efficiency [97].

Conversely, the environmental sustainability dimension is concerned with the analysis and implementation of organizational actions aimed at reducing the effects of waste releases and the use of energy and natural resources. According to Rusinko [98], environmental dimensions include materials, energy, emissions, wastes, and resource consumption.

The analysis and implementation of organizational operation—with the goal of optimizing the well-being of both internal and external stakeholders—constituted the third

dimension, known as social sustainability. Social sustainability, at a macro-level, emphasizes how communities or societies live; it is about equity and basic needs. At the micro or firm level, issues related to employees' working conditions, health, and safety are the major dimensions [99].

4. Findings of Bibliometric Data

4.1. Continent and Country of Origin

The screened and reviewed articles were also mapped into categories in terms of their country of origin and continent, and the results are reported in Figure 2. For studying the country of origin, the first author's location was utilized for the analysis, which was based on the occurrence of frequency to maintain uniformity across all recognized entries. The findings indicated that the attention given region-wise varies from continent to continent. Among the reviewed papers, the record shows that 61% (43 in number) were published in Europe (EUR), 21% (15) in North America (NA), followed by Asia (AS) at 10% (7), from South America (SA) it was 6% (4), and Australia (AUS) was 1% (1). The top six countries that contributed their results, published in 43 papers within the fields of AM and SCs, are from Europe, namely, the UK with 28% (12 papers), and the Netherlands, Italy, and Finland with 12% each (5 papers). Germany and Denmark have 7% (3 in total) of the European contribution in these subject areas. In the research areas, the USA has the highest percentage of articles from North America (87%, 13 in total). However, when it comes to the African continent, it indicates that there has been little research done in the field of additive manufacturing in the context of supply chains.

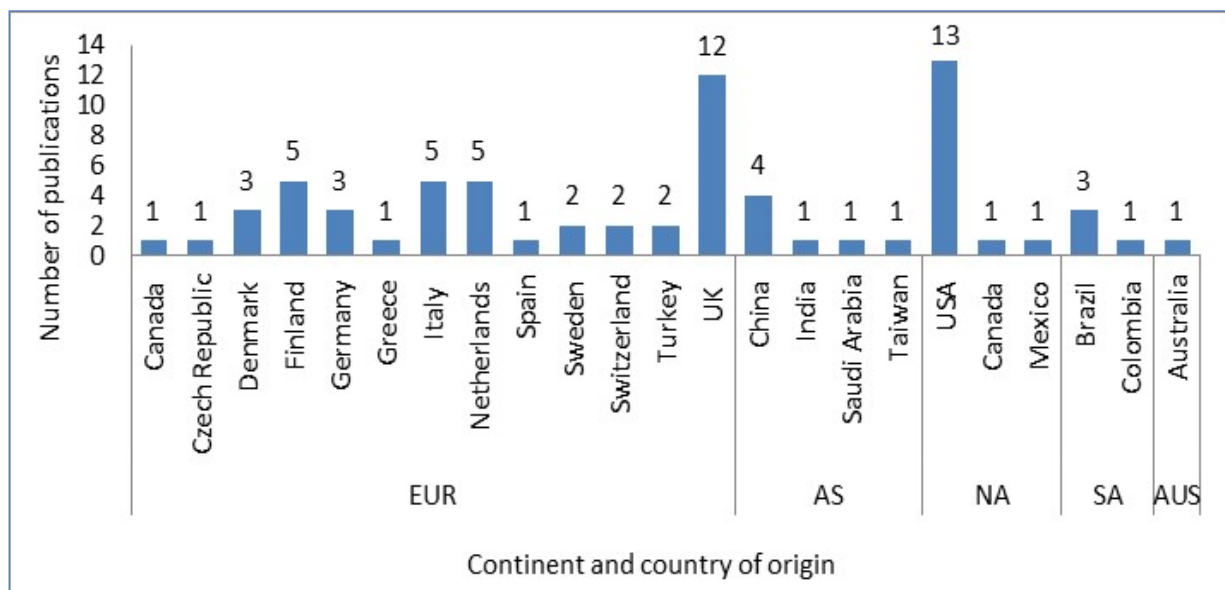


Figure 2. Number of publications per continent and country.

4.2. Publishers Contributions and Publication Trends

The findings reported in Figure 3a show the distribution of articles in the areas of AM impacts in a SC context on publishers' data bases. The results indicated that most of the articles are covered by Taylor and Francis at 23% (16 papers), followed by Elsevier at 22% (15 papers) and Emerald at 20% (14 papers). On the other hand, Figure 3b illustrates the trends of published articles per year. The result shows an increasing trend from 2013 to 2021 on the topic areas. The top publication years on the topic of the impacts of AM on the supply chain are 2016, 2017, 2018, 2019, 2020, and 2021.

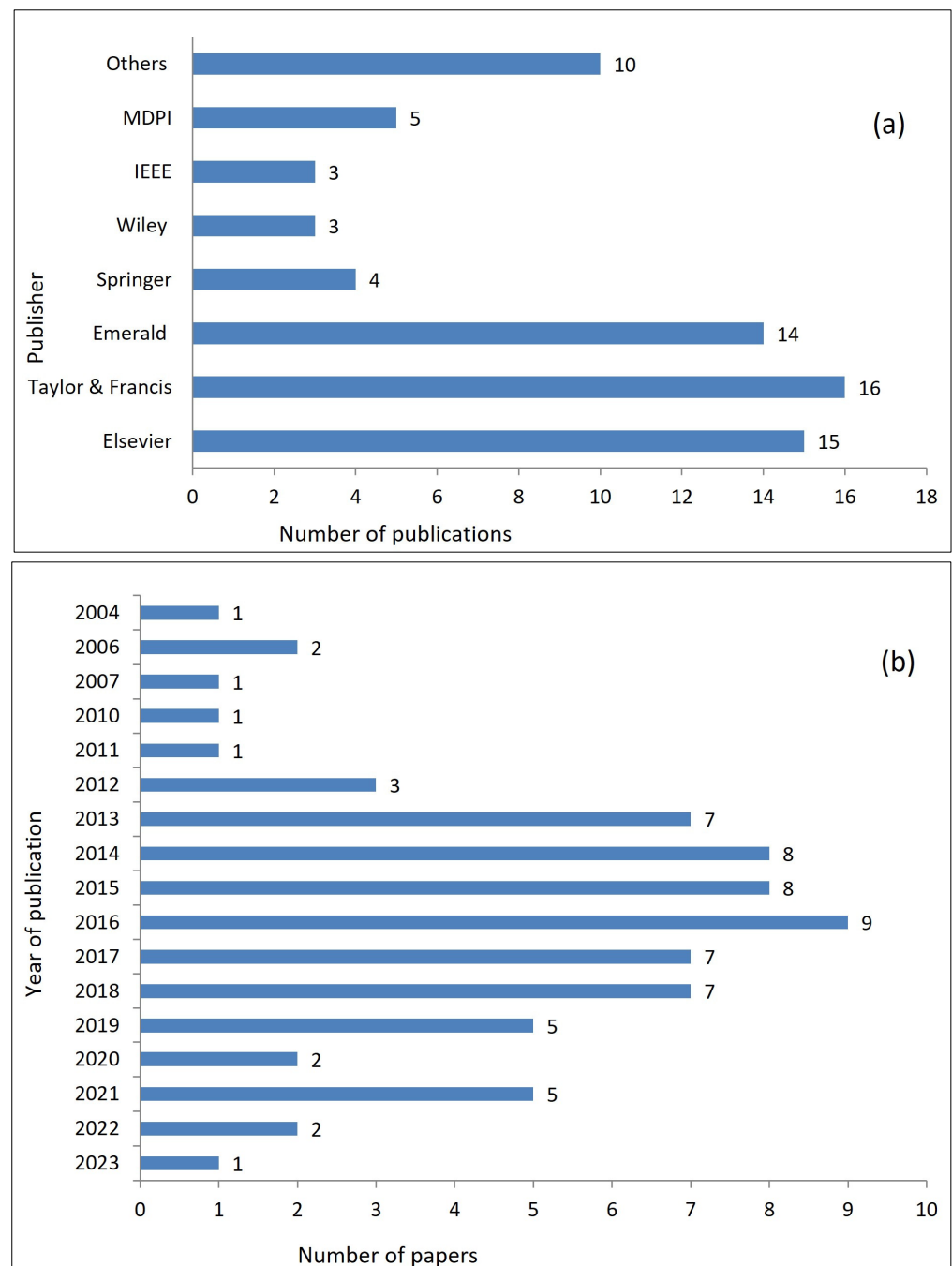


Figure 3. (a) List of publishers and (b) publication trends.

4.3. Study by Types of Industry

Figure 4 illustrates the publications or study areas by the types of industry, and the findings revealed that 12% (7) of the study was conducted in healthcare product manufacturing industries and aircraft industries; 9% (4) in automotive industries; on aggregate, 26% (15) of the study was conducted in other types of manufacturing industries, like cable grommet manufacturers, lamp manufacturers, pipe fitting manufacturing companies, modular and bespoke products manufacturers, notebook and smart phone industries, consumer goods, injection molding, and fuel injectors manufacturers; 4% (2) was in electronic equipment production companies and fashion industries; and on aggregate, 25% (14) of the studies were conducted in service-giving industries, including distribution agents, consumer good companies, wholesalers, retailers, and transportation and logistics service-

providing sectors; and 2% (1) was in the construction sectors. This indicated that there is a lack of or limited research in the areas of construction and fashion industries, especially in footwear-making industries.

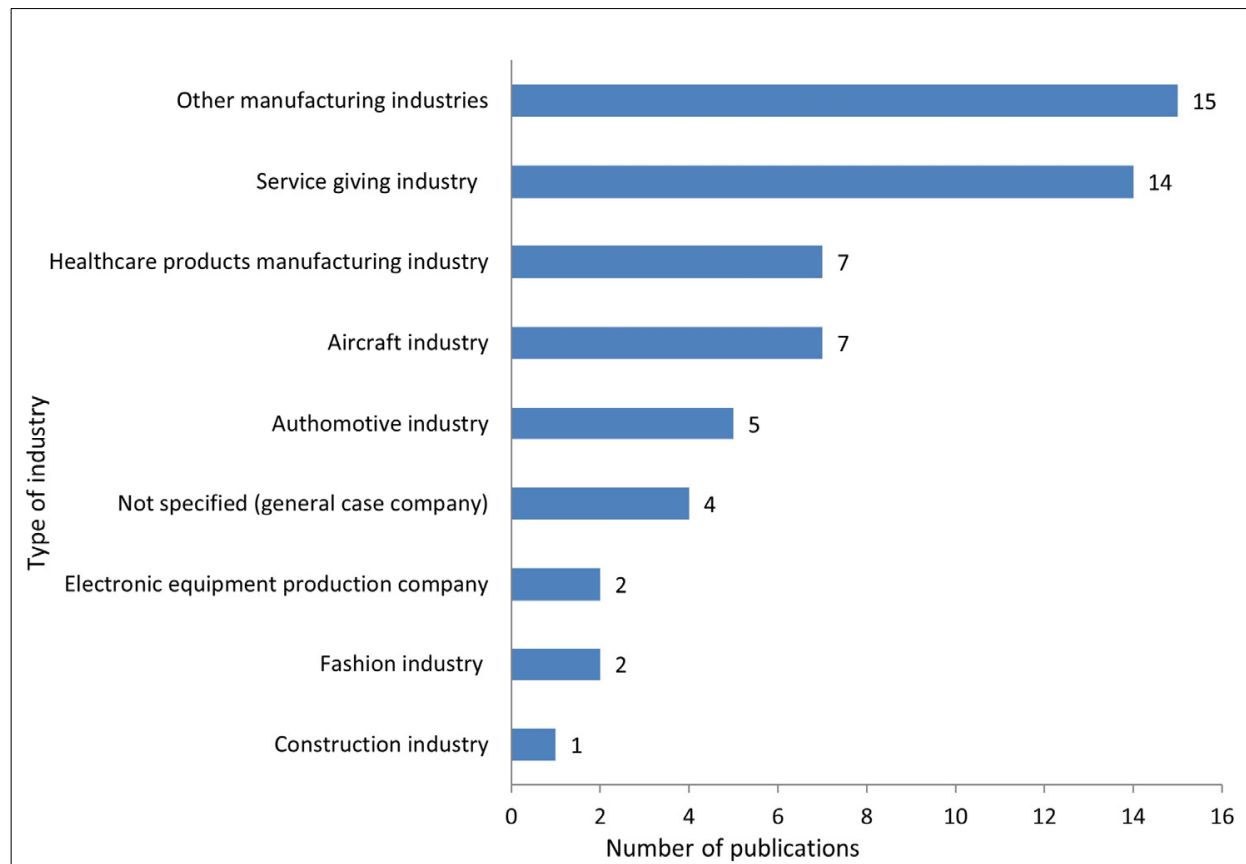


Figure 4. Publications per types of industry.

4.4. Additive Manufacturing Technology Best Practices in SC Context

From the detailed overview of the existing reviewed papers in this study, the best practices of AM impact in the SC context have been identified and classified into six factors as follows:

- SC efficiency and firm performance;
- Cost-related factors;
- Time-related factors;
- Inventory-related factors;
- Flexibility and manufacturing-related factors;
- Energy, environmental, and waste-related factors;
- The details of these factors are presented in the following subsections.

4.4.1. Time- and Cost-Related Factors

Figure 5a shows the findings of the reviewed papers in terms of the time-related factors, where the results illustrated that, among the identified impacts of AM in SC time-related factors, the cumulative lead time represents 52%(14 in number) and is ranked in the first stage (most frequently mentioned or reported in the literature). Delivery times were at 15% (4), while the setup, changeover, and production times represented 7% (2) and ranked in the third stage. Supplier time, downtime, and the time taken to the market represented 4%(1) and ranked in the last stage. Thus, comparatively, AM has attracted the most interest in reducing the cumulative lead, delivery, setup, changeover, and production time of SCs.

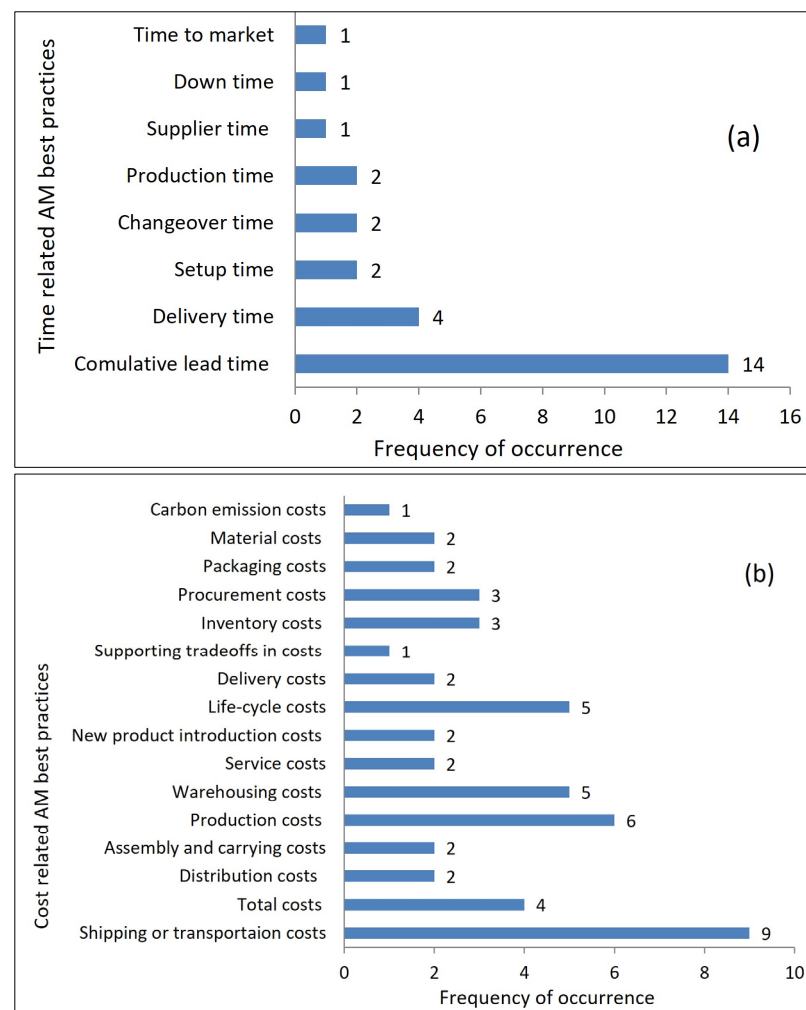


Figure 5. (a) Time-related factors; (b) cost-related factors.

On the other hand, Figure 5b illustrates the main findings of this paper on the impacts of AM in the SC context that is related to cost factors. The result summarized the findings according to the frequency of occurrence in each paper, and the outcome indicated that shipment or transportation costs represented 18% (9) and ranked first, while production costs at 12% (6) ranked in the second stage. In addition, the result revealed that warehousing and life-cycle costs represented 10% (5 each) and ranked in the third stage, followed by inventory and procurement costs with 6% (3); packaging, material, new product introduction, distribution and assembly, delivery cost, and service cost ranked 4% (2 each), and carbon emission and supporting tradeoff costs ranked at a 2% (1) representation. From this, it is possible to state that AM has shown the most in terms of its impacts on transportation, production cost, warehousing, and life-cycle costs, which have the highest frequency of occurrence.

4.4.2. Inventory, Marketing (Flexibility), and Manufacturing-Related Factors

Figure 6a shows the overview of the significant impacts of AM on SCs in relation to inventory factors. The ranking, according to the frequency of occurrence in the existing literature, indicated that safety stock represents 39% (9) and inventory level reductions represent 26% (6), ranked in the first stage, making transport less intensive. Reducing the flow of goods, at 13% (3), ranked in the second stage; achieving postponement benefits in inventory management, at 9% (2), ranked in the third stage. Reducing the material distribution, implementing a build-to-order strategy, and reducing nonvalue-adding activities, at 5% (1), ranked in the next stage. This may imply that, among the factors considered, AM is

considered to have a great impact in reducing safety stock and inventory levels, making transport less intensive and reducing the flow of goods.

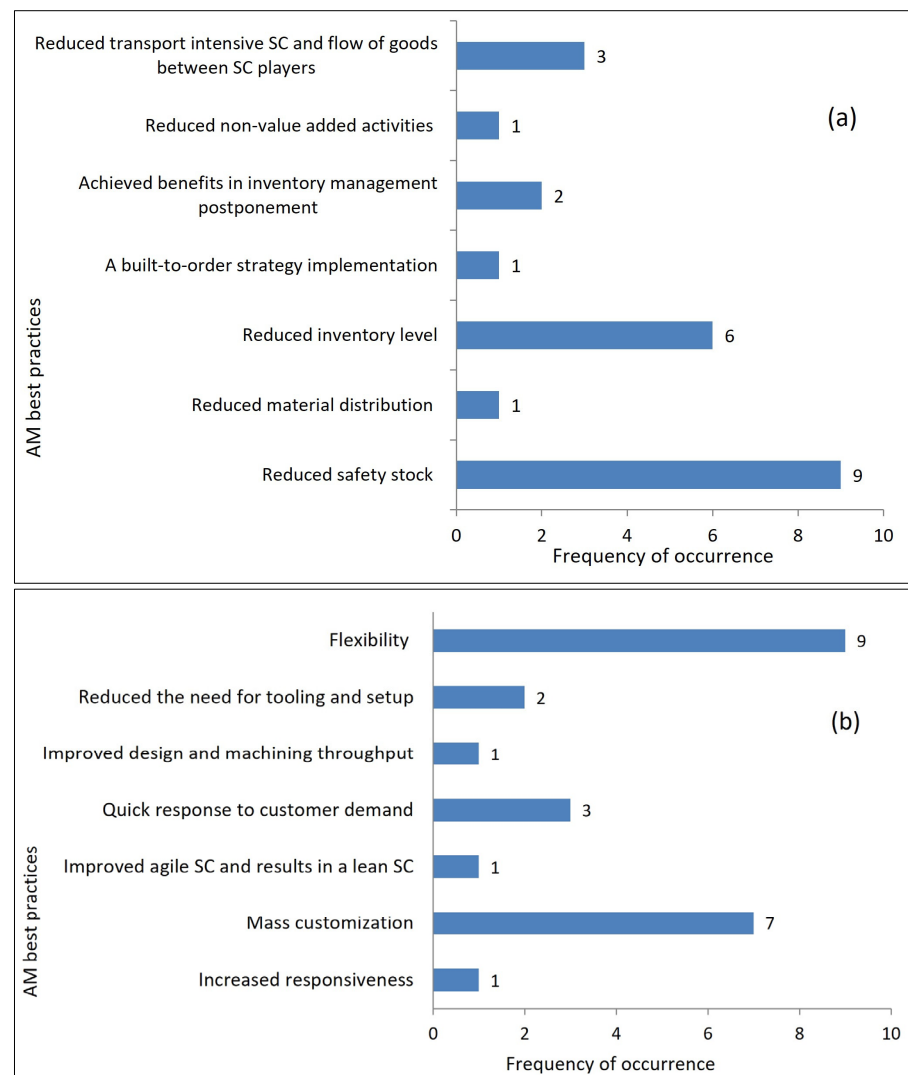


Figure 6. (a) Inventory-related factors; and (b) marketing (flexibility) and manufacturing-related factors.

The reviewed results concerning marketing and manufacturing flexibility related impacts of AM on SCs are illustrated in Figure 6b. This overview also indicates that AM has a great influence on manufacturing flexibility, improving mass customization, quickly responding to customer demands, and eliminating the need for new tooling and setups to introduce new products into the production system.

4.4.3. Energy, Environment Waste, SC Efficiency, and Firm Performance-Related Factors

The energy, environment, and waste-related impacts of AM on SCs are other issues that are focused on in this study (Figure 7a). The results of the review, according to the frequency of occurrence in the published materials, illustrated that waste reduction scored the highest (43%), while a reduction in life-cycle energy consumption ranked in the second stage with 36% frequency, and greenhouse gas emission scored 14%, coming in at third position. Therefore, the energy, environmental, and waste-related factors of AM may have a great impact on reducing waste, energy consumption, and CO₂ gas emissions.

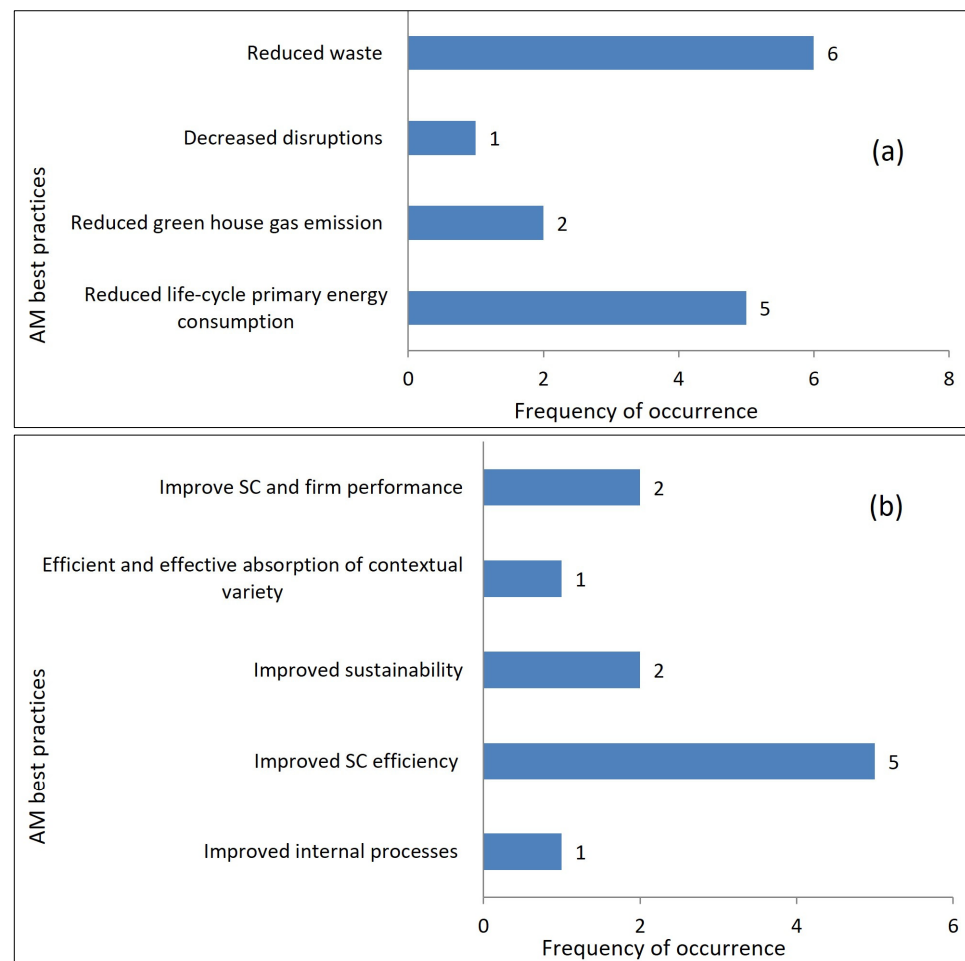


Figure 7. (a) Energy and waste-related factors; (b) SC efficiency and firm performance-related factors.

In a related context, the impacts of AM on SCs related to efficiency and firm performance factors are analyzed and illustrated in Figure 7b. The finding of this part indicated that improving SC efficiency ranked the highest (46%), improving firm performance and sustainability ranked in the second stage at 18%, and contextual variety and improving internal SC process ranked in the third stage at 9%. From this, it is possible to conclude that AM has great potential in improving SC efficiency and firm performance.

5. Discussions and Future Research Directions

The outcome of this study revealed that a larger percentage (26%) of the studies focused on manufacturing sectors like cable grommet lamps and pipe fittings manufacturers. This shows the importance of AM in the supply chain of these sectors. On the other hand, limited research interest was observed in the fashion and construction sectors. The availability or distribution of studies region-wise varies from continent to continent. In this area, the findings of this paper show limited research works in Africa, while a significant number of studies were observed from Europe.

Furthermore, the outcome of this study illustrated the simplification of SCs after implementing AM, which is identical to the assertion of Li et al. [65], who illustrated the effectiveness of AM in providing a high variety of products to meet customer demand on time. According to our findings, through AM, parts are produced on demand without the requirements of tooling and setups, creating an opportunity to participate with customers in product design. This will not only change the procurement process but also reduce the complexity of products and the supply risk. Furthermore, our study findings indicated that AM has a great impact in reducing safety stock and inventory levels, improving

mass customization, quickly responding to customer demands and market uncertainty, and eliminating the need for a new production line for introducing new products in the production system. This makes transport less intensive and reduces the flow of goods. According to the study by Mia et al. [92], these have great potential to improve a SC's efficiency and a firm's performance.

From the perspectives of the environmental sustainability dimension, the existing studies reported in [21,23] illustrated its impacts in reducing environmental related problems. For the same issues, our study revealed that implementation of AM has a favorable environmental impact on the SC network by reducing product weights, transportation, carbon emissions, material wastes, and waste generation, and reducing disruptions and carbon emissions in the supply networks. In addition to these, complicated products are produced in near-net shapes, and this resulted in little waste and sustainability improvement, and it eliminates the need for energy-intensive, inefficient, and environmentally damaging manufacturing methods.

In terms of the economic feasibility of AM, the findings of our study revealed that adaptation of AM attracted the most interest in reducing delivery, setup, and changeover and production times of SCs. Among others, it breaks down SCs into the smallest components, and as a result, the system efficiency is improved by cutting down on the distribution, carrying, assembly, and component costs. It also maximizes customization and reduces the costs related to inventory holding, stock-outs, warehousing, packaging, and logistics. We also observed that the research by Mohsen [42] and Milad et al. [46] evaluated the economic feasibility of AM in terms of time- and cost-related factors, respectively. Confirming our findings, their study results illustrated the benefits of implementing AM in reducing time- and cost-related factors in SC systems.

According to Thomas [88] and Peter [89], the implementation of AM creates new opportunities for firms' SCs for quick responses to unexpected events and disruption, and to react quickly and flexibly to customer requests. In these regards, the findings of our work identified the benefits of implementing AM in improving market disruptions against the flexibility of volume, mix, and delivery.

Furthermore, this review paper qualitatively elaborated on how AM improves SCs in terms of time, cost, inventory, flexibility, and reducing the number of stages. We observed that some existing studies indicated the impact of AM on SCs, and this depends on different factors where its benefits vary from industry to industry or sector to sector. Based on the conducted systematic review work, this study identified the following areas for possible future research directions:

- [1] Quantitative studies can illustrate the strength and relationship between additive manufacturing best practices and supply chain elements.
- [2] Establishing in-depth knowledge of the key additive manufacturing best practices that affect supply chain elements.
- [3] Investigating the implication of implementing AM with a SC perspective in developing countries.
- [4] Identifying the variables that affect SCs in the AM industry and their benefits.

Thus, to fill the knowledge gap in the area, this study identified six AM best practices and developed a conceptual framework, as illustrated in Figure 8. The developed conceptual framework demands that practitioners and industries rate the identified six AM best practices according to their importance from a SC perspective. Through this conceptual framework, researchers, industries, or practitioners can identify and prioritize the most significant AM best practices that impact their supply chain.

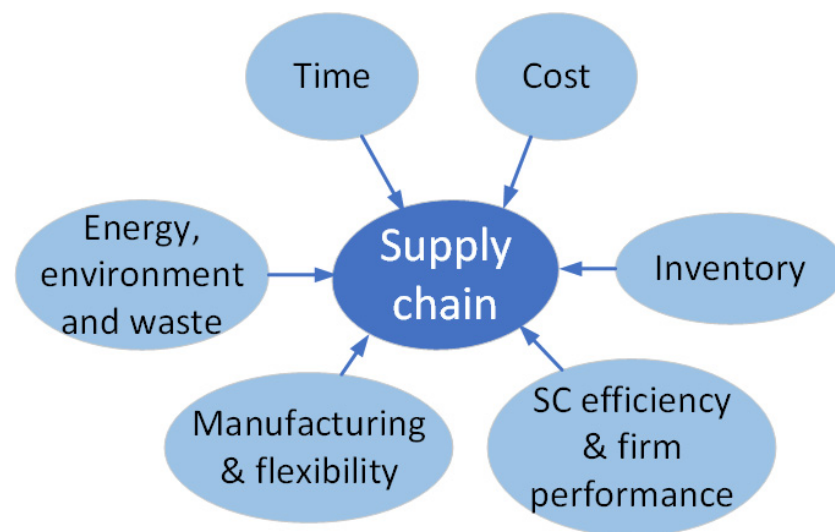


Figure 8. Conceptual frameworks of AM factors having an impact on the supply chain.

6. Conclusions

In this literature review, the state-of-the-art study of additive manufacturing impacts within a supply chain context has been examined and reported. The literature data were collected from online databases, and 70 papers were identified through the manual screening of 978 retrieved papers. By addressing the three TBL dimensions, the main benefits of AM on SCs were pointed out, identified, and classified into different factors. Based on the frequency of occurrence in each paper, the detailed impacts of AM on SCs were illustrated. In addition, this study highlighted the publication trends per type of industry and year of publication and the most contributed countries. Finally, gaps were identified, the conceptual framework was developed, and future directions were proposed.

According to this study, there has been a noticeable increase in the previous ten years in the amount of research conducted on AM in the context of supply chains, demonstrating a growing interest in this subject area. Secondly, the study outcome signifies that most of the research has been conducted in developed countries. This shows a lack of knowledge and the availability of limited studies in developing countries. This opens a good opportunity for researchers to conduct their study in developing countries like Ethiopia, where this review work can be implemented to fill this knowledge gap.

In addition, the findings of this study highlighted the dominant focused industries in this field of study area. This will support the development and testing of theories in the process of identifying trends and best practices across a range of industrial sectors. On the other hand, the outcome of this study illustrated the environmental, economic, and societal impacts of AM on the supply chain. The identified best practices are ranked according to the frequency of occurrence in each paper and classified into six major factors. Based on the findings, this paper illustrated that AM has attracted the most interest for its impact on cost, time, inventory, manufacturing, energy, environment, and firm performance-related factors. This will help researchers, practitioners, or industries to understand the behavior of the AM effects within a SC context in transforming traditional manufacturing methods. In addition, the outcome of this will help researchers rate the identified factors according to their importance from a supply chain perspective.

Finally, even if this paper identified and confirmed the best practices of AM in the SC context in transforming the TM supply chain, there are limitations in this technology in terms of quality control, printed-part defects, mechanical properties, and the like. Moreover, this technology depends on the types of products or parts in transforming TM. Thus, in our continuing research, we would like to focus on these and other related issues to fill the observed knowledge gap.

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