Impact of 3-D Printing Technology in Manufacturing Supply Lines to Improve Resilience During Black Swan Events

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Abstract - Globalized networks of suppliers and manufacturing hubs may fail in the face of high impact and unpredictable events such as Hurricane Katrina, the 9/11 terrorist attack, the Fukushima disaster and the COVID-19 pandemic—known as black swan events. I examine how 3-D printing, a now widespread and powerful technology, may be relevant in this context. I show 3-D printing in the manufacturing sector will simplify complex and globalized networks thereby making them more resilient to black swan events. The findings of this review article are important for managers and chief supply chain officers in that they can better simplify the chains through the adoption of 3-D printing infrastructure, thereby insulating their businesses from the cascading effects of black swan events. I find support for the hypothesis that the adoption of 3-D printing infrastructure in manufacturing supply chain infrastructure leads to simplification of the networks. It facilitates simplification through economies of scale, customization, co-production, better demand prediction, freedom in shape design, allowance for manufacturing postponement, fewer nodes and integration of functionalities to reduce steps in the chain. These contribute to improved resilience through a variety of mechanisms.

Keywords: *3-D printing, additive manufacturing, black swan events, economies of scale, node structure, resilience.*

1. Introduction

An efficient supply chain facilitates the allotment of goods at a desired place and time in the required quality and quantity. With reduced margins due to high labour costs, increased competition and efficiency improvements in transport and reduced trade barriers, companies in the manufacturing sector have developed complex networks of supply lines and have shifted to using manufacturing bases in countries such as Mexico, Taiwan, Argentina and China. This allows the development of lean and just-in-time logistic operations, thereby providing competitive leverage in the hyper-competitive business landscape [1]–[3]. Traditional risks impacting the complex globalized supply chains arise from issues of distorted demand information and breakdowns in production, logistics and transportation, which can be recurrent and routine [4], [5]. Research suggests that almost 75% of all organizations each year experience supply chain disruptions [6], [7].

1.1. Black swan events- COVID-19

'Black swan' events pose substantially greater problems. These are huge magnitude events which are pervasive, unpredictable and that necessitate re-shaped economic structures. Examples include the shortage of automobile parts that disrupted production lines for several months in Japan after the 2011 tsunami, the floods in Thailand in 2011 that affected the supply chains of computer manufacturers due to a shortage of hard disks, or the 2010 eruption of a volcano in Iceland that disrupted air transportation and impacted time-sensitive air shipments [8]–[10]. Black swan events may be thought of as 'unknown unknowns' impacting supply chains in ways not accounted for in existing business models, including shortages of parts, the need for changes to product design, manufacturing stoppages and other logistical breakdowns [11]. 3-D is another name for additive manufacturing (AM) since in AM the layers are added according to the digital design as opposed to the subtractive manufacturing wherein the material is extruded in the processes of milling, lathing or by numerical control machines [12].

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Although 3-D printing has been known in academic circles since the 1980s, only recently have costs of these printing machines come down such that their adoption in the manufacturing industry has expanded. The costs of 3-D have further reduced costs of digital designs through open sourcing by the global community RepRap, the open-source Lulzbot TAZ manufactured by Aleph Objects and the largest consumer 3-D printing company, MakerBot [13]–[19].

1.2. Impact of 3-D printing on the supply chain verticals

Research before 2014 focused on the use of this technology for improving operational efficiencies of conventional industrial manufacturing through enhancement in rapid prototyping and speciality manufacturing (e.g., making injection moulds for conventional manufacturing) [20], [21]. Since 2014, research on the impact of 3-D printing on supply chains has burgeoned. 3-D printing is emerging as a general-purpose technology with broad implications for supply chains (e.g., predicted to be $21 billion in the U.S alone in 2021). Examples include Dubai aiming at 25% 3-D in all new buildings by 2030 [22], customized dosage printing of medicines as in the case of Spritam (used for treating epilepsy) which was approved by Food and Drug Administration (FDA) in 2015 [23], bioprinting of tissues or medical devices [24] , and tool-less manufacturing of complex, precision automobile or aviation components [17], [25]–[28]. Further research is needed to specify the relationship between simplification of chains due to 3-D technology adoption in the manufacturing sector. The purpose of this literature review is to examine whether 3-D printing in the manufacturing sector will simplify complex and globalized networks thereby making them more resilient to black swan events and thus making the manufacturing process more resilient. The findings of this review article are important for managers and chief supply chain officers in that they can better understand supply chain risk management to protect their businesses. This review highlights how they can approach risk identification, assessment, mitigation and monitoring by leveraging the advantages of 3-D printing [29].

2. Literature Review

The study looks into secondary data (collected from authentic data sources both public and private) sources. The thorough literature review to examine how the design of supply networks can be simplified to improve resilience to black swan events through the use of 3-D printing helps to better substantiate our argument. The desire to look for solutions to disrupted supply chains in the wake of COVID-19 pandemic led to an initial literature search. The need for this thematic narrative review was obvious due to a research gap on how the use of 3-D printing technology may improve supply chain resilience, especially in the manufacturing sector. The research design of this study has made use of the several datasets, conducting crucial appraisal of several research studies and analyzing the existing literature both qualitatively as well as quantitatively. The review process involved the identification, prioritization, synthesis, and analysis of the research evidence in the existing literature that related to the topics of the study with crucial attention to the findings that have been subsequently brought forward by the author. The research papers, journal publications and the articles used in this study aim to comprehend the research question and then post the analysis of the findings, address the problems as well as offer recommendations.

2.1. Identification, Selection and Evaluation of Eligible Literature

In order to analyze and interpret the topic of study, the secondary data was collected that focuses on the use of 3D printing in the manufacturing sector as well as impact of this technology on the design of the supply chains. and google scholar. The search was carried out using combinations of keywords including globalization, complex supply chains, supply chain design, black swan events, manufacturing supply chains, manufacturing automobiles, 3-D printing, additive manufacturing, resilience, disruptive technology, blockchain and multi-modal transport. Because the search was carried out using ProQuest Central, HBR, the Stanford University online library, MIT Journals and ResearchGate, there are books and trade magazines that might contain practical case studies and reports relating to the topic that were not included. This was not intended as an exhaustive review of the topic but instead sought to identify key papers that specifically link 3-D printing to manufacturing supply chain resiliency. An approximate number, 500 publications, articles and reports focusing on 3 D printing and its impact on supply chains were studied. Firstly, exclusion and inclusion criteria were applied to choose the recent papers. The majority (82%) were from 2014–2020 and were focused on 3-D printing and its advantages. Generally, earlier articles were more about supply chain design or the reasons for globalized networks. This mix of research from the past (supply chains without 3-D printing) and current (increasing adoption of 3-D printing in chains and their impact) was informative. Moreover, only the publications that were published in the English language were chosen and the articles that were written in other languages were not taken into consideration. Further, narrowing of the funnel involved drawing attention to the research type of the existing literature thereby having visibility into the authenticity of their works. After searching for these articles and applying the above selection criteria, 25 articles were chosen for the study.

2.2. Assessing the Quality and Appropriateness of The Literature Reviewed

The research approach used in this study involved the review of various articles thus creating a differentiation between the qualitative and quantitative research design. Moreover, a critical inductive investigation was carried out in each of the reviewed papers and the techniques of data collection used in each paper were also examined. The units of analysis for the articles were classified into individual, group, organization, tools and methods classes. Extensive research was carried out to focus on the articles that emphasized on how the use of 3D printing infrastructure would alter the design of the supply chains and result in simplification thereby making the chains resilient to disruptions. This review focused on the subject matter and the related sources were investigated as well.

2.3. Extraction and Synthesis

Descriptive analysis was used to reveal pattern or trend of any pre-existing propositions, theories, methodologies, and findings. A systematic and structured classification of the studies was done in this research approach wherein papers of various scholars were screened in terms of literature review, objectives, methodology, analysis and findings. Thereafter a critical review of each article helped in formulating patterns and specific themes of study. Personal insights were extracted from each article including the year of publications, the research methods, the directions of research outcomes and the data collection techniques.

3. 3-D Printing Process Methodology

Three-dimensional (3-D) printing is a technology used for fabricating complex standalone parts or assemblies (for use in the manufacturing process) in a printer from their digital design through AM, wherein a single or multiple material are used to print layer over layer with the shape of each layer to be adjusted to form the intended component [30], [31]. The process of AM is shown in Figure 1, wherein the metallic powder is melted with a high heat laser or an electric-arc and this molten metal is then deposited in layers as directed by the controller to form the shape of the part [32]. This technology has led to reduced product development times and faster-time-to-market compared to traditional manufacturing [33]. It allows for building complex components, provides freedom from design constraints and offers capabilities for a single integrated assembly line for different parts [32], [34]–[36].

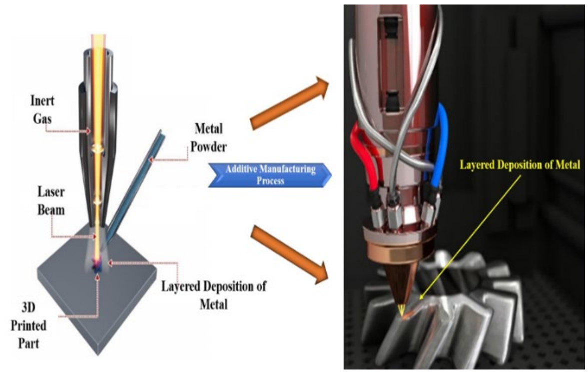

Figure 1: Additive manufacturing process using high heat laser

The latest 3-D printers are increasingly efficient, e.g., with faster precision printer heads that provide competitive advantages compared to injection moulding processes. Further, the integration of 3-D printing infrastructure with cloud manufacturing facilitates users in accessing a variety of on-demand services. The complete 3-D infrastructure requires setting up a design centre or integration with a design institute through cloud services that would enable the consumer to participate in the selection or the design phase. Subsequently, as shown in Figure 2, a 3-D CAD (computer-aided design) followed by a software file is created which is then sliced in a software application to decide on the granularity of the layers of deposition of the 3-D material.

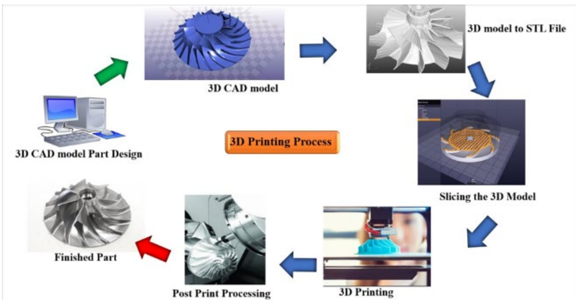

Figure 2: 3-D printing process

Finally, the design is produced in a 3-D printer and is thereafter sent to a conventional post-processing machine [36]. Moreover, a system of manufacturing as a service for 3-D printing provides a platform for free design which is helpful in co-customizing and making it possible to have many smaller production sites close to customers thereby simplifying chains [37]–[39].

4. 3-D Infrastructure in Manufacturing Supply Chain

The global 3-D market will grow to $35.6 billion by 2024, with a healthy adoption outlook for 3-D printing in the manufacturing sector [40]. The metal used in the field increased by 42% in 2018, a fifth straight year of increase, implying growing use of 3-D printing in the manufacturing sector [41]. In a survey carried out by PricewaterhouseCoopers (PwC), of more than 100 manufacturing companies in 2014, 11% had already switched to volume production of 3-D-printed parts or products, with the sale of industrial-grade printers at one-third the volume of sales [42]. The automobile sector too is mobilizing significant investment for manufacturing and installing electric vehicle supply equipment (EVSE) infrastructure globally [43]. 3-D printers and Co-customization would help in augmenting and better development of such electric vehicle production supply lines. This consist of both charging and battery swapping technologies. These numbers reflect the inclination of the manufacturing industry to leverage the advantages of 3-D printing.

4.1. Co-Customization

In traditional manufacturing supply chains, customization of a product adds complexity to supply chains because of the additional variables that must be introduced [44]. However, the use of 3-D printing in a manufacturing chain, because of flexibility in shape design and storage of digital designs in the system, results in enhanced customization scope. In the contemporary business landscape, the options to the customer for configuring a product is almost a requirement of marketing and production departments, to create personalized products and enhance the customer experience. Adoption of 3-D printing blends adaptability (the ability to produce customer-specific products) with the low per-unit cost of mass-manufacturing [45].

For example, Husqvarna (supplier of outdoor power products for forest, parks and garden care) is a customer of Fast Radius, a 3-D manufacturing company with its own digital platform and a design innovation institute. Hewlett Packard also leverages the platform of Fast Radius to co-customize designs for its internal consumption as well as its customers. Partnering with Fast Radius has helped Husqvarna shorten its supply lines and lead times, as without 3-D printing it would take weeks (or more) to replenish supply [46]. Customers can participate in the design iterations— a type of co-production, without adding additional complexity in the chains[26], [47], [48].

Further, mass personalization requires the production hub to be supported in the processes of concept design, function prototyping, complete prototyping and engineering sample production. Mass personalization in production requires companies to adopt smart manufacturing which entails the use of the information systems and communication technology to integrate distributed factories as part of the production service. Each of these connected factories would have agile manufacturing consisting of 3-D printers along with a set of conventional workstations and flexible transport systems for the manufacturing of a set of different types of products on the same line (making such a system more resilient to disruptions). The smart factory, integrated with information communication technology and 3-D printers along with conventional production machines in the line, would result in a manufacturing process that is more adaptable to the personalized production and mass customization in the entire process of product development from product design to initial production [31].

4.2. Optimal Balance Between Centralization and Distribution of Nodes

A manufacturing supply chain consists of nodes that are independent decision-making business entities such as manufacturers, warehouses, transportation carriers and financial institutions, all looking to maximize profit within the scope of their operations. These nodes are connected with links which may be interdependencies, supply-demand relationships, material flow, logistics or partnerships—all of which can be highly nonlinear, multiscale and complex [49], [50]. This was aptly communicated by Tom Linton, chief procurement and supply-chain officer at Flextronics ‘I have 14,000 suppliers. I guarantee that with 14,000 suppliers, at least one of them is not performing well today’ [51]. Research shows that the greater the number of nodes and links in a chain, the greater the severity of impact due to black swan events because of increased exposure [52]. Recent examples include (1) the worldwide disruption of plastic car parts due to an explosion in a chemical plant in Germany in 2012 and (2) SARS in 2003 and COVID-19 in 2020, disrupting the flow of automobile parts and other components in manufacturing chains from China and across Asia that impacted companies globally [53]–[59].

There is a trade-off between the pooling of nodes which reduces the cost of mitigating recurrent risks (although with diminishing marginal returns) and diversification of nodes which reduces the impact of black swan events (again with marginal diminishing returns of adding the nodes). This case was exemplified in the differential impact on the supply chains of Nokia and Ericsson—both customers of Phillips—by the destruction of the Phillips factory by fire in 2000 in New Mexico. Immediately after the incident, Nokia started sourcing its chips from other American and Japanese suppliers since Nokia practised a multiple-supplier strategy (diversified nodes). By contrast, Ericsson employed a single-source policy (pooling of nodes) and was challenged since it had no other supplier of chips [60]. Chandra et al. (2019) suggest that agile chains can better adapt to the disruptive impacts of black swan events and are more resilient. Rylands et al. (2016) and Durach et al. (2017) highlight that 3-D printing leads to enhanced agility in supply chains because even if the pooled critical nodes are disrupted, the on-demand and in-situ manufacturing would enable the supply chain to adapt and recover. The application of 3-D infrastructure reduces steps of manufacturing since the user or factory hubs can manufacture the parts rather than waiting for their arrival. As such, companies can improve their rebound potential following disruptive events[61]–[64].

4.3. Freight Concentration and Volume Through Nodes

It is not only the number of nodes and links but also the concentration of freight that flows through a few critical nodes in the supply lines that affect the vulnerability of chains. Concentrating the freight through a few port hubs saves costs but increases the risk [61], [65]. Furthermore, compression of the time of activity (reduced order cycle times and lower inventory levels) at these nodes increases the vulnerability of the globalized chains [66]. In such a situation, a disruption that affects one segment of this chain will impact it entirely—from supplier to customer in the case of supplier-driven systems and backwards from customer to manufacturer in the case of demand-driven ones [67]. 3-D printing reduces freight volume through nodes and changes the inventory mix from components to raw material (powder, filament coils and liquids) since the physical flow of goods would be replaced by digitized designs for on-demand production at the location of consumption [68]. Chen (2016) pointed out that 3-D printing could shift production hubs from Asia to North America. Such a paradigm shift, due to localized manufacturing facilitated by AM or DMHAM (see below), would result in a decline in shipping and air cargo. Moreover, reduction in freight volumes and the replacement of physical goods with digital inventories would result in lower inventory storage thereby simplifying demand for 3-D printing logistic materials that might be supplied by 3-D printer equipment companies, third party suppliers or from the original producers [69].

4.4. In-Situ, On-Demand and Postponement of Production

At a certain point in a ‘leagile’ (a chain design that is the combination of lean nature for stable demand and agile nature for volatile demand) supply chain, management needs to transition between agile and lean efficiencies—labelled a decoupling point. Whenever the company faces highly volatile demand at the decoupling point, as in the case of any black swan event, the supply chain needs to be agile enough to accurately capture consumer needs in terms of demand planning [70], [71].

The implementation of 3-D printing in a manufacturing supply chain facilitates the processes of manufacturing by producing closer to the point of consumption thereby simplifying long and complex chains (in-situ production), by allowing manufacturing to be delayed to a later stage in the delivery (postponement) rather than manufacturing at individual supplier platforms, improving flexibility and by producing only on-demand by the consumer[24], [28], [63], [72], [73]. Philips on its 125th anniversary, partnering with Twikit's platform, provided 125 of its customers the opportunity to customize and personalize their face shavers (each person could select the colour, texture and form of the external grip) from a palette of options which were then produced at Philips's 3-D printing facilities. This postponed the customized product to the time of consumption. This model of 3-D printing postponement can be used to stock up the inventory of the base products that can be finished as per the customized requirements of the customer late in the process [74]. 3-D printing aids in distributing deployment of digital manufacturing capacity in small batches which results in saving a considerable amount of inventory by postponing the creation of a variety of products to the last link in the chain thereby avoiding compromised delivery times [75], [76].

4.5. Reduction in Process Steps and Reduced Lead Times

In the current process of mass manufacturing, a process called injection moulding is often used. It requires several parts, and these may be manufactured by different vendors who are geographically dispersed and therefore exposed to black swan event disruptions in their supply lines. 3-D printing removes these manufacturing complexities while creating fewer, smaller and better-performing components resulting in fewer assembly steps, leading to swifter production cycles and lower manufacturing costs [74], [77]. 3-D printing facilitates faster tooling, storage and re-use of digital designs and, most importantly, the localization of the source of the raw materials [78]–[80]. The importance of in-situ AM manufacturing is highlighted in an example wherein first responders in an emergency can greatly reduce production logistics by simply delivering aluminium powder (a key raw material for AM) rather than establish a long supply chain for other materials [81]. Another example of in-situ AM is the digital manufacturing network of Hewlett Packard through which it works with several customers, including Jaguar, Land Rover and Vestas (which makes wind turbines), to manufacture in-situ parts through 3-D printing [46].

4.6. Digitized Inventory

The use of 3-D infrastructure in a chain enables the replacement of physical inventory by a digital one thereby effectively moving the point of distinction of the product parameters further downstream to the point of use. This obviates the need for variety in stock thus reducing inventory levels and improving part availability. On-demand generation combined with the availability of digital designs would result in the readiness of the part at a lower cost at the point of use, even when the traditional chains are disrupted due to black swan events [68], [82]–[89]. An organization that adopts 3-D in its manufacturing process would need a robust ERP (enterprise resource planning) system that facilitates storage, transfer and use of digital components for in-situ production. A database of such digitized parts would also help the managers in the organization determine a build location decision based on the costs and risk analysis of the production of such parts in the chain. Components may be produced in-house, using conventional or 3-D, or parts are ordered from external suppliers [90]. In the use of digitized inventory, the supply chains will be shortened, thereby removing the risks in planning, shipping and stockpiling that are necessary when preparing for unforeseen events [24], [69].

4.7. Digital Manufacturing-Assisted Hybrid AM (DMHAM)

The adoption of AM in a production line results in the manufactured part having a rough surface finish and inaccurate dimensional tolerances, which is a challenge for the adoption of AM technology in its pure form [91], [92]. To overcome this manufacturing process challenge, the concept of hybrid AM is being implemented. In this, a metal part is near-net produced (initial production of the item is so close to the final shape that it reduces the need for surface finishing) through the AM and thereafter post-processed via legacy techniques, such as grinding and milling [93]. An example of direct metal rapid tool manufacturing 3-D printer process is shown in Figure 3. It utilizes inert/active gas welding for additive 3-D printing and then uses computer numeric controlled milling for the subtractive process to produce a near-net shape [94]. Facilitated by a DM-assisted hybrid AM platform, the processes of additive manufacturing combined with subtractive manufacturing, in a single unit and controlled by computer numeric programs, results in producing a cheaper and higher quality part that may substantially reduce production steps.

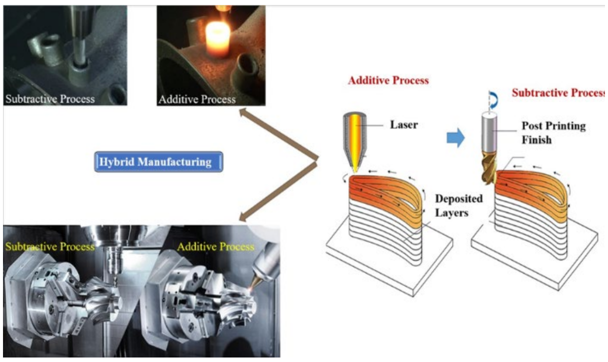

Figure 3: Hybrid-layered manufacturing for making metallic dies and moulds

An algorithm for operation sequencing of additive, subtractive and inspection processes for manufacture may be used to run the processes serially or in parallel to enhance overall capabilities [73], [94]. A major impact of the DM-assisted hybrid AM would be the facilitation of distributed manufacturing in which the parts may be manufactured at diverse geographic locations thereby shortening transportation distances [93], [95]. Further, DMHAM would facilitate the development of smart factories whose traditional subtractive manufacturing centres may create low-cost, high-volume parts complemented by critical parts through 3-D printing[95], [96]. In the 3-D printing hubs, the low volume parts are produced to order and thereafter are sent to nearby machining shops for surface finish. However, with the adoption of the DMHAM technology, the surface finish would be carried out in the same machine thereby shortening the chain. In the conventional process, these components would be manufactured in different machines or procured from a supplier (increasing the lead time as well as adding complexity to the chain) whereas in the DMHAM all these components are near-net produced as one part and thereafter polished in the same machine. Furthermore, the DMHAM technique would facilitate repair of parts (anything from large aircraft engines to automobile parts) that may not be possible with AM alone thereby simplifying or obviating the need for reverse logistic supply chains [93].

4.8. 4-D printing

Whilst 3-D printing has resulted in large batch customized printing of parts and assemblies at the location of production, 4-D printing (which currently is in nascent stages of industrial application) has the potential to enable 3-D-printed parts further. 4-D can be used to transform part shapes in response to environmental stimuli, e.g., properties of self-assembly or self-healing are being utilized in the automobile industry to simplify chains [97]. The supply chains can be simplified by reducing spare requirements post-sales by incorporating spares at the time of production. These would then be activated to self-assemble if the original part breaks, thereby obviating the need for supply or assembly efforts. Moreover, self-healing of critical hoses, pipes or gaskets reduces the need for supplying these physically in supply chains [98]–[100].

4.9. Smart Contracts With 3-D Printing Infrastructure

Manufacturing chains become more resilient by having 3-D printing hub centres under 'smart contracts' in the critical path of the chain [11], [61]. Blockchain technology, due to disintermediation as one of its benefits, may be used for the implementation of smart contracts with the several suppliers instead of relying on one single supplier at all tiers. This provides for more responsive and real-time switching to the backup suppliers in case of stoppages in the chain due to Black Swan events. Smart contracts also result in reduced lead times, increased visibility, trust and security in the network and therefore increase overall resilience [101], [102]. Equally important, in the onset of a disruptive event, the affected parts of the globalized chains may be replicated in triggering the smart contract that already exists in the decentralized secure ledger of blockchain between the company and an AM bureau hub to produce disrupted critical parts. This would increase the resilience of chains because it will automatically shift to localized production centres [103].

4.10. Production in Long Tails

A manufacturing long tail as shown in Figure 4, i.e., the statistical representation of a power-law distribution, in which the head represents the popular products and tail depicts niche or low-demand products in markets [103]. 3-D printing enables the more efficient production of parts represented in the tail of this graph. An example of the long tail niche that does not have mass consumption is in the aerospace industry. SpaceX rapidly produced (reducing the period from months in traditional manufacture to just a couple of days) stronger, more ductile and reliable valve bodies for its space rocket engines using 3-D printing. In using 3-D printing, the NASA supply chains were simplified since thousands of engine parts were 3-D printed closer to the launch site rather than all over the globe. These niche parts were produced at a fraction of cost since these could be produced in small batches [74]. Thus, AM will support such long-tail production in remote geographical locations that may see disruptions from black swan events.

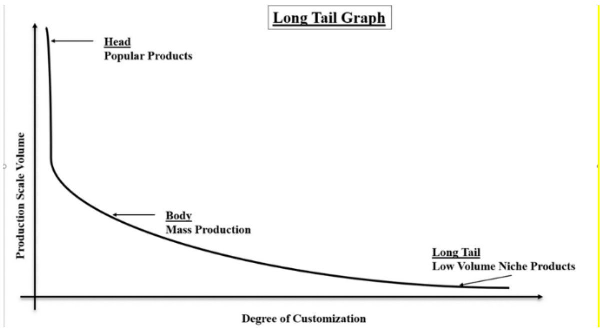

Figure 4: Example of manufacturing long tail graph

4.11. Prosumers

Most companies in healthcare and consumer goods have leveraged 3-D printing to reconfigure their supply chains to facilitate wide availability of options for the consumer base, including capitalizing on the benefits of reduced costs of 3-D printing hardware, transportation costs, carbon offset benefits and an exponentially growing database for printable objects [35], [104]–[106]. 3-D printing infrastructure in supply chains facilitates the movement of components as digital designs over the internet rather than the physical parts through a manufacturing chain. This process results in improved flexibility, speed and resilience in the chain [107]. In this co-creation process of 3-D printing in the supply chain, customers themselves can partake in the design or development process and thus become prosumers, and the manufacturing shifts from centralized production to micro-manufacturing [45], [69]. The incentive alignment and decision synchronization collaboration between two or more partners has mutual benefits, helping anticipate and manage disruptions in a chain [24].

4.12. Blockchain enabled 3-D and supply chain Management.

Blockchain technology works on distributed data structure based on transactions in a peer-to-peer network wherein the blocks are linked by cryptographic algorithms and each node has the copy of the transaction thereby making the transaction records immutable [108]. Blockchain technology may be used by companies to support peer-to-peer logistic tracking information to enhance chain visibility [64]. Moreover, due to immutability of record storage across nodes, it can be used to secure the data generated in the intelligent machines, cyber-physical assets and intelligent transportation systems resulting in improved security and resilience against black swan events [109], [110]. The structure of blockchain is decentralized creating multiple copies, thereby greatly reducing the risk of a cyber-attack from hackers on a single database [111]. Blockchain technology may help companies in making the chains more resilient by removing intermediaries to enhance the chain efficiency and reduce network complexities and by transforming standalone manufacturing into decentralized or open manufacturing. It may also provide for mapping of chains to provide knowledge at critical junctures at the onset of an unpredictable event, shifting sourcing patterns away from the blocked or unsuitable sources to suitable ones [112].

5. Results of the Review

Three-dimensional (hereafter 3-D) printing is one technology to increase resilience and offset the costs due to such disruptions. The 3-D process may enhance the resilience of manufacturing supply chains to risks posed by black swan events. It makes the chains simpler by enabling consumers or factories to directly produce goods using printers and digital designs thereby obviating the need for steps between raw material and consumers that are necessary for traditional manufacturing chains. Moreover, on-site printing of parts simplifies logistical considerations and administrative preparation and the digitization of the part design removes the need for intermediate warehouses or complex multi-modal links [113], [114].

6. Discussion

The concept of resilience is well entrenched in diverse fields such as the study of material objects returning to original shape after the application of stress, environmental ecosystem ecology or societal rebound in communities after an economic setback. Whereas enterprise resilience strategies work well against predictable recurrent risks, the unknown risks present due to black swan events are best dealt with when supply chains are designed through collaboration, flexibility and visibility[115]–[117]. In their research on the supply chain resilience, Hosseini and Khaled (2019) highlight that among all the nodes—such as sources of raw materials, product design and engineering organizations, manufacturing plants, distribution centres, retail outlets, customers and transportation—the weakest link in a supply chain in the onset of a black swan event is the suppliers. This was exemplified when Hsinchu industrial park in Taiwan (critical supplier of 10% of world's computer memory chips) was struck with a devastating earthquake, resulting in shortage of microchips affecting global companies such as Dell, Gateway, IBM, Apple and HP.

6.1. AM leads to merged phases of production.

With 3-D printing in the manufacturing process, the movement of components through the chains is in the form of digitized engineering rather than the physical part itself, bypassing exposed suppliers to improve resilience in the chain [107], [118].

3-D printing in manufacturing supply chains introduces accurate and frequently updated visibility of demand because customers can partake in the development process thereby becoming prosumers with the manufacturing only on product demand [45], [69], [70] —thereby improving resilience in chains [118]. The introduction of AM in manufacturing merges the distinction between the phases of product design and manufacture, resulting in shortened supply lines. Also, co-customized production enhances the capabilities for specialized parts or healthcare products, making supply chains more resilient [119]–[121], including during the COVID-10 pandemic [122].

6.2. 3-D printing results in reduced lead times with distributed manufacturing.

Research shows that increased lead times in supply chains results in decreased resilience [123]. The massive floods in Ayutthaya, a manufacturing-centric province in Thailand, or the massive earthquake in Tohoku, Japan, both disrupted the flow of parts for Toyota automobile manufacturing for months [124], [125]. In both cases, the lead times of such parts would have been greatly reduced by the adoption of 3-D printing in the chain since it would enable the production of such parts in the Toyota plant via on-site manufacturing [79], [126], [127]

. The diminishing margins in manufacturing and evolution in the way we do business has led brick-and-mortar businesses and manufacturing companies to globalize. This complicates sourcing (e.g., supplier tiers and contracts), including the emerging need to leverage and extract advantages from all corners of the globe. Customers have added to the complexity by demanding greater customization of products, wanting these products faster (one day to one-hour deliveries), shortening product life cycles and increasing switching frequency across products and brands.

The supply chain can be considered to have five key business processes: planning, sourcing of raw materials, production of parts, deliveries and returns. The hardest hit of these five business processes (having a cascading effect on the entire chain) are the sourcing, production and deliveries [128]. As supply chains become more globalized, their exposure to the impact of any one black swan event is greatly increased in any one component of sourcing, production and deliveries. Adoption of 3-D printing infrastructure mitigates such risks and improves resilience by facilitating distributed manufacturing (in-situ or at-home production), shortening long supply chains by the digitization of inventory and reducing processing steps. Chains are more responsive and flexible through smart contracts and production capability closest to market of mass-customized products, facilitating delivering precisely what a customer wants, where and when they want it.

7. Conclusion.

3-D printing reduces the complexity of supply chains by reducing the inventory in a system. 3-D printing also replaces several assembly steps with single tasks thereby reducing process complexity and simplifying chains. The simplification of supply chains by reducing the number of nodes and links, increasing visibility of demand, making manufacturing more flexible, co-creation with customer, and postponement all improve the resilience of chains. The induction of AM, as well as DMHAM techniques of 3-D printing and properties of self-assembly or self-healing in 4-D printing, provide even further advances. Perhaps COVID-19 and its impact on the supply lines across the globe will be the watershed event that results in a paradigm shift towards adopting 3-D printing for efficiency, transparency and agility in supply chains—a core way to render them more resilient to the effects of black swan events and for mitigating risks. The findings in this literature review show that chains can be simplified and made resilient to better withstand black swan events through the adoption of 3-D printing.

References

[1] G. Gereffi, "Global Value Chains and International Competition," *Antitrust Bull.*, 2011, doi: 10.1177/0003603X1105600104.

[2] M. Goyal, "Five reasons why auto world is shifting to emerging markets and what it means for India [automobiles]," *Economic Times*, May 19, 2013.

[3] H. Norihiko and Lee, "U.S. Car Makers Plan To Expand in China; Ford, GM Expect to Boost Manufacturing Capacity, Introduce New Products," *Asian Wall Street Journal*, Hong Kong, Oct. 17, 2003.

[4] A. Ghadge, M. Weiß, N. D. Caldwell, and R. Wilding, "Managing cyber risk in supply chains: a review and research agenda," *Supply Chain Management*. 2019, doi: 10.1108/SCM-10-2018-0357.

[5] A. R. Singh, P. K. Mishra, R. Jain, and M. K. Khurana, "Design of global supply chain network with operational risks," *International Journal of Advanced Manufacturing Technology*. 2012, doi: 10.1007/s00170-011-3615-9.

[6] C. Breunig and B. D. Jones, "Stochastic process methods with an application to budgetary data," *Polit. Anal.*, 2011, doi: 10.1093/pan/mpq038.

[7] K. Scholten, P. Sharkey Scott, and B. Fynes, "Building routines for non-routine events: supply chain resilience learning mechanisms and their antecedents," *Supply Chain Manag.*, 2019, doi: 10.1108/SCM-05-2018-0186.

[8] R. Aggarwal and J. Bohinc, "Black swans and supply chain strategic necessity," *J. Transp. Secur.*, 2012, doi: 10.1007/s12198-011-0080-5.

[9] Y. Sheffi and J. B. Rice, "A supply chain view of the resilient enterprise," *MIT Sloan Management Review*. 2005.

[10] G. A. Zsidisin and S. M. Wagner, "DO PERCEPTIONS BECOME REALITY? THE MODERATING ROLE OF SUPPLY CHAIN RESILIENCY ON DISRUPTION OCCURRENCE," *J. Bus. Logist.*, 2010, doi: 10.1002/j.2158-1592.2010.tb00140.x.

[11] Y. Mukai, T. Fujimoto, and Y. W. Park, "'Virtual dual sourcing' of specialized goods: Lessons from supply chain disruption of Riken and Epson Atmix," *J. Enterp. Inf. Manag.*, 2019, doi: 10.1108/JEIM-10-2014-0098.

[12] J. Griffey, "Chapter 1. introduction.," *Libr. Technol. Rep.*, vol. 53, no. 5, pp. 5–11, 2017, [Online]. Available: https://search.proquest.com/docview/2285241839?accountid=158986.

[13] C. Bosqué, "What are you printing? Ambivalent emancipation by 3D printing," *Rapid Prototyp. J.*, 2015, doi: 10.1108/RPJ-09-2014-0128.

[14] J. Morton, "Emergent, affordable 3-D printing technology:Engineering, geology, mineralogy, metallurgy, chemistry, etc.," *Eng. Min. J.*, vol. 217, no. 12, pp. 58–60, 2016, [Online]. Available: https://search.proquest.com/docview/1854287792?accountid=158986.

[15] J. P. J. De Jong and E. De Bruijn, "Innovation lessons from 3-D printing," *MIT Sloan Manag. Rev.*, 2013, doi: 10.1109/emr.2014.6966948.

[16] B. Savonen, T. Mahan, M. Curtis, J. Schreier, J. Gershenson, and J. Pearce, "Development of a Resilient 3-D Printer for Humanitarian Crisis Response," *Technologies*, 2018, doi: 10.3390/technologies6010030.

[17] H. J. Steenhuis and L. Pretorius, "Consumer additive manufacturing or 3D printing adoption: An exploratory study," *J. Manuf. Technol. Manag.*, 2016, doi: 10.1108/JMTM-01-2016-0002.

[18] J. M. Pearce, "Low-Cost 3D Printers Are Growing Up," *Machine Design*, Cleveland, Feb. 15, 2017.

[19] V. P. Seidel, B. Langner, and J. Sims, "Dominant communities and dominant designs: Community-based innovation in the context of the technology life cycle," *Strateg. Organ.*, 2017, doi: 10.1177/1476127016653726.

[20] T. Caffrey and T. Wohlers, "Additive manufacturing state of the industry," *Manuf. Eng.*, 2015.

[21] S. Vinodh, G. Sundararaj, S. R. Devadasan, D. Kuttalingam, and D. Rajanayagam, "Agility through rapid prototyping technology in a manufacturing environment using a 3D printer," *J. Manuf. Technol. Manag.*, 2009, doi: 10.1108/17410380910984267.

[22] E. Cangelli and M. Conteduca, "Architettura on demand. Nuovi scenari per il progetto e l'industria delle costruzioni TT - Architecture on demand. New scenarios for the design project and the construction industry," *Techne*, 2018, doi: http://dx.doi.org/10.13128/Techne-23036.

[23] M. Ramola, V. Yadav, and R. Jain, "On the adoption of additive manufacturing in healthcare: a literature review," *Journal of Manufacturing Technology Management*. 2019, doi: 10.1108/JMTM-03-2018-0094.

[24] C. S. Singh, G. Soni, and G. K. Badhotiya, "Performance indicators for supply chain resilience: review and conceptual framework," *J.*

Ind. Eng. Int., 2019, doi: 10.1007/s40092-019-00322-2.
[25] T. Duda and L. V. Raghavan, "3D metal printing technology: the need to re-invent design practice," *AI Soc.*, 2018, doi: 10.1007/s00146-018-0809-9.
[26] D. R. Eyers and A. T. Potter, "E-commerce channels for additive manufacturing: An exploratory study," *J. Manuf. Technol. Manag.*, 2015, doi: 10.1108/JMTM-08-2013-0102.
[27] F. Pascucci, A. Perna, A. Runfola, and G. L. Gregori, "The Hidden Side of 3d Printing in Management *," *Symphonya*, 2018, doi: 10.4468/2018.2.08.
[28] M. Ruffo, C. Tuck, and R. Hague, "Make or buy analysis for rapid manufacturing," *Rapid Prototyp. J.*, 2007, doi: 10.1108/13552540710719181.
[29] C. Colicchia, A. Creazza, and D. A. Menachof, "Managing cyber and information risks in supply chains: insights from an exploratory analysis," *Supply Chain Manag.*, 2019, doi: 10.1108/SCM-09-2017-0289.
[30] A. Ghilan, A. P. Chiriac, L. E. Nita, A. G. Rusu, I. Neamtu, and V. M. Chiriac, "Trends in 3D Printing Processes for Biomedical Field: Opportunities and Challenges," *Journal of Polymers and the Environment*. 2020, doi: 10.1007/s10924-020-01722-x.
[31] H. S. Kang, S. Do Noh, J. Y. Son, H. Kim, J. H. Park, and J. Y. Lee, "The FaaS system using additive manufacturing for personalized production," *Rapid Prototyp. J.*, 2018, doi: 10.1108/RPJ-11-2016-0195.
[32] M. P. Hong, W. S. Kim, J. H. Sung, D. H. Kim, K. M. Bae, and Y. S. Kim, "High-performance eco-friendly trimming die manufacturing using heterogeneous material additive manufacturing technologies," *Int. J. Precis. Eng. Manuf. - Green Technol.*, 2018, doi: 10.1007/s40684-018-0014-9.
[33] M. Hlavin, "3-D Printing: The Next INDUSTRIAL REVOLUTION.," *Appl. Des.*, 2014.
[34] J. S. Akmal, M. Salmi, A. Mäkitie, R. Björkstrand, and J. Partanen, "Implementation of industrial additive manufacturing: Intelligent implants and drug delivery systems," *J. Funct. Biomater.*, 2018, doi: 10.3390/jfb9030041.
[35] C. F. Durach, S. Kurpjuweit, and S. M. Wagner, "The impact of additive manufacturing on supply chains," *Int. J. Phys. Distrib. Logist. Manag.*, 2017, doi: 10.1108/IJPDLM-11-2016-0332.
[36] H. I. Medellin-Castillo and J. Zaragoza-Siqueiros, "Design and Manufacturing Strategies for Fused Deposition Modelling in Additive Manufacturing: A Review," *Chinese J. Mech. Eng.*, vol. 32, no. 1, p. 53, Dec. 2019, doi: 10.1186/s10033-019-0368-0.
[37] A. Ben-Ner and E. Siemsen, "Decentralization and Localization of Production: The Organizational and Economic Consequences of Additive Manufacturing (3D Printing)," *Calif. Manage. Rev.*, 2017, doi: 10.1177/0008125617695284.
[38] A. Gholamipour-Shirazi, M. A. Kamlow, I. T. Norton, and T. Mills, "How to formulate for structure and texture via medium of additive manufacturing-a review," *Foods*. 2020, doi: 10.3390/foods9040497.
[39] L. Guo and J. Qiu, "Combination of cloud manufacturing and 3D printing: research progress and prospect," *Int. J. Adv. Manuf. Technol.*, 2018, doi: 10.1007/s00170-018-1717-3.
[40] "The Wohlers Report 2019," *Met. Powder Rep.*, 2019, doi: 10.1016/j.mprp.2019.05.018.
[41] J. Jayaram, A. Amling, A. Chaudhuri, and D. McMackin, "Prime time for additive manufacturing," *Supply Chain Manag. Rev.*, vol. 24, no. 2, pp. 36–43, 2020, [Online]. Available: https://search.proquest.com/docview/2375711359?accountid=158986.
[42] R. D'Aveni, "The 3-D printing revolution," *Harvard Business Review*. 2015.
[43] A. Serohi, "Importance of Battery Recycling & Swapping: The Next Inevitable Step in EV Supply Chain," *Int. J. Supply Chain Manag.*, vol. 10, no. 1, pp. 1–20, 2021, doi: doi.org/10.6084/m9.figshare.14132261.v2.
[44] F. Salvador, M. Rungtusanatham, and C. Forza, "Supply-chain configurations for mass customization," *Prod. Plan. Control*, 2004, doi: 10.1080/0953728042000238818.
[45] V. Verboeket and H. Krikke, "Additive Manufacturing: A Game Changer in Supply Chain Design," *Logistics*, 2019, doi: 10.3390/logistics3020013.
[46] A. Hand, "How 3D Printing Is Changing Production Models," *Automation World*, Chicago, Aug. 09, 2019.
[47] T. Rayna and L. Striukova, "From rapid prototyping to home fabrication: How 3D printing is changing business model innovation," *Technol. Forecast. Soc. Change*, 2016, doi: 10.1016/j.techfore.2015.07.023.
[48] M. A. Waller and S. E. Fawcett, "Click here to print a maker movement supply chain: How invention and entrepreneurship will disrupt supply chain design," *Journal of Business Logistics*. 2014, doi: 10.1111/jbl.12045.
[49] C. R. Carter, D. S. Rogers, and T. Y. Choi, "Toward the theory of the supply chain," *J. Supply Chain Manag.*, 2015, doi: 10.1111/jscm.12073.
[50] A. Serohi, "Sustainable Supply Chain of Automobile Sector: A Literature Review," *Int. J. Supply Chain Manag.*, vol. 9, no. 6, pp. 82–87, 2020, [Online]. Available: https://ojs.excelingtech.co.uk/index.php/IJSCM/

article/view/5142.
[51] G. A. Zsidisin and M. Henke, Eds., *Revisiting Supply Chain Risk*, vol. 7. Cham: Springer International Publishing, 2019.
[52] C. Martinez, "Supply Chain Risks, Resilience and Firm Performance: An Empirical Study," University of Maryland, College Park, 2018.
[53] L. L. Goedhals-Gerber, "The composite supply chain efficiency model: A case study of the Sishen-Saldanha supply chain," *J. Transp. Supply Chain Manag.*, 2016, doi: 10.4102/jtscm.v10i1.209.
[54] Y. Liu, J. M. Lee, and C. Lee, "The challenges and opportunities of a global health crisis: the management and business implications of COVID-19 from an Asian perspective," *Asian Bus. Manag.*, 2020, doi: 10.1057/s41291-020-00119-x.
[55] Z. Y. Liu, C. Li, X. Y. Fang, and Y. B. Guo, "Energy Consumption in Additive Manufacturing of Metal Parts," *Procedia Manuf.*, vol. 26, pp. 834–845, 2018, doi: 10.1016/j.promfg.2018.07.104.
[56] O. Vaidya and M. Hudnurkar, "Multi-criteria supply chain performance evaluation: An Indian chemical industry case study," *Int. J. Product. Perform. Manag.*, 2013, doi: 10.1108/17410401311309195.
[57] Y. Sheffi, "Modeling Risks in Supply Chains," in *Finance and Risk Management for International Logistics and the Supply Chain*, 2018.
[58] Y. Wang and F. Zhang, "Modeling and analysis of under-load-based cascading failures in supply chain networks," *Nonlinear Dyn.*, 2018, doi: 10.1007/s11071-018-4135-z.
[59] L. Zhu, X. Ren, C. Lee, and Y. Zhang, "Coordination contracts in a dual-channel supply chain with a risk-averse retailer," *Sustain.*, 2017, doi: 10.3390/su9112148.
[60] M. M. H. Chowdhury and M. Quaddus, "Supply chain readiness, response and recovery for resilience," *Supply Chain Manag.*, 2016, doi: 10.1108/SCM-12-2015-0463.
[61] S. Chopra and M. S. Sodhi, "Reducing the risk of supply chain disruptions," *MIT Sloan Manag. Rev.*, 2014.
[62] M. Pournader, K. Rotaru, A. P. Kach, and S. H. Razavi Hajiagha, "An analytical model for system-wide and tier-specific assessment of resilience to supply chain risks," *Supply Chain Manag.*, 2016, doi: 10.1108/SCM-11-2015-0430.
[63] I. Ul Haq and F. Franceschini, "Distributed manufacturing," *Benchmarking An Int. J.*, 2019, doi: 10.1108/bij-05-2019-0204.
[64] C. Wu and D. Barnes, "Design of agile supply chains including the trade-off between number of partners and reliability," *Int. J. Adv. Manuf. Technol.*, 2018, doi: 10.1007/s00170-018-2205-5.
[65] S. Saad, Z. M. Udin, and N. Hasnan, "Dynamic supply chain capabilities: A case study in oil and gas industry," *Int. J. Supply Chain Manag.*, 2014.
[66] A. Mckinnon, "BUILDING SUPPLY CHAIN RESILIENCE: A Review of Challenges and Strategies," *Int. Transp. Forum Discuss. Pap.*, 2014.
[67] H. Escaith, "Trade Collapse, Trade Relapse and Global Production Networks: Supply Chains in the Great Recession," *SSRN Electron. J.*, 2011, doi: 10.2139/ssrn.1497512.
[68] S. Mohr and O. Khan, "3D Printing and Its Disruptive Impacts on Supply Chains of the Future," *Technol. Innov. Manag. Rev.*, 2015, doi: 10.22215/timreview942.
[69] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Bus. Horiz.*, 2017, doi: 10.1016/j.bushor.2017.05.011.
[70] J. D. Nel and J. A. Badenhorst-Weiss, "Supply chain design: Some critical questions," *J. Transp. Supply Chain Manag.*, vol. 4, no. 1, Nov. 2010, doi: 10.4102/jtscm.v4i1.68.
[71] T. Althaqafi, "The Impact of State-of-the-Art Supply Chain Management Practices on Operational Performance," *Int. J. Supply Chain Manag.*, vol. 9, no. 5, pp. 1286–1291, 2020, [Online]. Available: https://ojs.excelingtech.co.uk/index.php/IJSCM/article/view/4452.
[72] J. DiBiasio, "Bookend: Manufacturing meets the web - Makers: The new industrial revolution (Random House, 2012), By Chris Anderson," *Asian Invest.*, 2013.
[73] S. Khajavi, J. Holmström, and J. Partanen, "Additive manufacturing in the spare parts supply chain: hub configuration and technology maturity," *Rapid Prototyp. J.*, 2018, doi: 10.1108/RPJ-03-2017-0052.
[74] L. Pannett, *Supercharg3d : How 3D Printing Will Drive Your Supply Chain*. wiley, 2019.
[75] P. Appelqvist and E. Gubi, "Postponed variety creation: Case study in consumer electronics retail," *International Journal of Retail and Distribution Management*. 2005, doi: 10.1108/09590550510622281.
[76] L. Vega and L. Mesa, "INTEGRACIÓN DE LA IMPRESIÓN 3D EN EL PROCESO DE CERA PERDIDA PARA LA PRODUCCIÓN DE JOYAS, CON FINES DE ESTANDARIZACIÓN," *Inf. Técnico*, vol. 83, no. 1, pp. 65–79, Jan. 2019, doi: 10.23850/22565035.1933.
[77] D. Woodlock, "How Advanced 3D Printing Technology is Driving the Future of Appliance Manufacturing," *Appl. Des.*, vol. 67, no. 1, pp. 34–35, 2019, [Online]. Available: https://search.proquest.com/docview/2172568925?accountid=158986.
[78] N. De la Torre, M. M. Espinosa, and M.

Domínguez, "Rapid Prototyping in Humanitarian Aid To Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan," *Human Factors and Ergonomics In Manufacturing*. 2016, doi: 10.1002/hfm.20672.

[79] S. S. Moore, K. J. O'Sullivan, and F. Verdecchia, "Shrinking the Supply Chain for Implantable Coronary Stent Devices," *Ann. Biomed. Eng.*, 2016, doi: 10.1007/s10439-015-1471-8.

[80] J. S. Srai *et al.*, "Distributed manufacturing: scope, challenges and opportunities," *Int. J. Prod. Res.*, 2016, doi: 10.1080/00207543.2016.1192302.

[81] A. S. Brown, "Chain reaction," *Mechanical Engineering*. 2018, doi: 10.1115/1.2018-OCT1.

[82] Z. Chen, "Research on the Impact of 3D Printing on the International Supply Chain," *Adv. Mater. Sci. Eng.*, 2016, doi: 10.1155/2016/4173873.

[83] J. Holmström and J. Partanen, "Digital manufacturing-driven transformations of service supply chains for complex products," *Supply Chain Manag.*, 2014, doi: 10.1108/SCM-10-2013-0387.

[84] N. A. Meisel, C. B. Williams, K. P. Ellis, and D. Taylor, "Decision support for additive manufacturing deployment in remote or austere environments," *J. Manuf. Technol. Manag.*, 2016, doi: 10.1108/JMTM-06-2015-0040.

[85] J. H. Mikkola and T. Skjøtt-Larsen, "Supply-chain integration: Implications for mass customization, modularization and postponement strategies," *Production Planning and Control*. 2004, doi: 10.1080/0953728042000238845.

[86] F. Pérès and D. Noyes, "Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments," *Comput. Ind.*, 2006, doi: 10.1016/j.compind.2006.02.010.

[87] R. I. Van Hoek, "Rediscovery of postponement a literature review and directions for research," *J. Oper. Manag.*, 2001, doi: 10.1016/S0272-6963(00)00057-7.

[88] S. Yang and Y. F. Zhao, "Additive manufacturing-enabled design theory and methodology: a critical review," *International Journal of Advanced Manufacturing Technology*. 2015, doi: 10.1007/s00170-015-6994-5.

[89] C. Weller, R. Kleer, and F. T. Piller, "Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited," *Int. J. Prod. Econ.*, 2015, doi: 10.1016/j.ijpe.2015.02.020.

[90] N. Kretzschmar, S. Chekurov, M. Salmi, and J. Tuomi, "Evaluating the readiness level of additively manufactured digital spare parts: An industrial perspective," *Appl. Sci.*, 2018, doi: 10.3390/app8101837.

[91] Y. Yang, Y. Gong, S. Qu, Y. Rong, Y. Sun, and M. Cai, "Densification, surface morphology, microstructure and mechanical properties of 316L fabricated by hybrid manufacturing," *Int. J. Adv. Manuf. Technol.*, 2018, doi: 10.1007/s00170-018-2144-1.

[92] D. . Marshall, "Assessing the Value of Supply Chain Information Sharing in the New Millennium," *Int. J. Supply Chain Manag.*, vol. 4, no. 4, 2015, [Online]. Available: http://ojs.excelingtech.co.uk/index.php/IJSCM/article/view/1144.

[93] D. Strong, M. Kay, T. Wakefield, I. Sirichakwal, B. Conner, and G. Manogharan, "Rethinking reverse logistics: role of additive manufacturing technology in metal remanufacturing," *J. Manuf. Technol. Manag.*, 2020, doi: 10.1108/JMTM-04-2018-0119.

[94] L. Chong, S. Ramakrishna, and S. Singh, "A review of digital manufacturing-based hybrid additive manufacturing processes," *Int. J. Adv. Manuf. Technol.*, 2018, doi: 10.1007/s00170-017-1345-3.

[95] D. Strong, M. Kay, B. Conner, T. Wakefield, and G. Manogharan, "Hybrid manufacturing – integrating traditional manufacturers with additive manufacturing (AM) supply chain," *Addit. Manuf.*, 2018, doi: 10.1016/j.addma.2018.03.010.

[96] W. S. Chu *et al.*, "From design for manufacturing (DFM) to manufacturing for design (MFD) via hybrid manufacturing and smart factory: A review and perspective of paradigm shift," *Int. J. Precis. Eng. Manuf. - Green Technol.*, 2016, doi: 10.1007/s40684-016-0028-0.

[97] A. Petrulaityte, F. Ceschin, E. Pei, and D. Harrison, "Applying Distributed Manufacturing to Product-Service System Design: A Set of Near-Future Scenarios and a Design Tool," *Sustainability*, 2020, doi: 10.3390/su12124918.

[98] M. H. Ali, A. Abilgaziyev, and D. Adair, "4D printing: a critical review of current developments, and future prospects," *Int. J. Adv. Manuf. Technol.*, 2019, doi: 10.1007/s00170-019-04258-0.

[99] M. Mahto and B. Sniderman, "4D printing: a critical review of current developments, and future prospects," *MIT Sloan Blogs*, Cambridge, May 2019.

[100] Z. Zhang, K. G. Demir, and G. X. Gu, "Developments in 4D-printing: a review on current smart materials, technologies, and applications," *Int. J. Smart Nano Mater.*, 2019, doi: 10.1080/19475411.2019.1591541.

[101] K. Christidis and M. Devetsikiotis, "Blockchains and Smart Contracts for the Internet of Things," *IEEE Access*. 2016, doi: 10.1109/ACCESS.2016.2566339.

[102] Y. Nakamura, Y. Zhang, M. Sasabe, and S. Kasahara, "Exploiting Smart Contracts for Capability-Based Access Control in the Internet

of Things," *Sensors*, vol. 20, no. 6, p. 1793, Mar. 2020, doi: 10.3390/s20061793.
[103] G. Gopal, A. G. Martinez, and J. M. Rodriguez, "Get smart with your contracts," *ISE Ind. Syst. Eng. Work*, 2018.
[104] M. Bogers, R. Hadar, and A. Bilberg, "Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing," *Technol. Forecast. Soc. Change*, 2016, doi: 10.1016/j.techfore.2015.07.024.
[105] E. Petersen and J. Pearce, "Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers," *Technologies*, 2017, doi: 10.3390/technologies5010007.
[106] G. Dwivedi, S. K. Srivastava, and R. K. Srivastava, "Analysis of barriers to implement additive manufacturing technology in the Indian automotive sector," *Int. J. Phys. Distrib. Logist. Manag.*, 2017, doi: 10.1108/IJPDLM-07-2017-0222.
[107] K. H. Queen, "Enabling a more flexible, less expensive, faster supply chain," *SMART Manufacturing*, Southfield, Jan. 2020.
[108] M. M. Queiroz, "A framework for sustainable supply chain in emerging economies," *Environ. Qual. Manag.*, vol. 28, no. 3, pp. 7–15, Mar. 2019, doi: 10.1002/tqem.21618.
[109] N. Kshetri, "Can Blockchain Strengthen the Internet of Things? By: Nir Kshetri Kshetri, Nir (2017). "Can Blockchain Strengthen the Internet of Things?"," *IEEE IT Prof.*, 2017.
[110] S. Yin, J. Bao, Y. Zhang, and X. Huang, "M2M security technology of CPS based on blockchains," *Symmetry (Basel).*, 2017, doi: 10.3390/sym9090193.
[111] S. Ølnes, J. Ubacht, and M. Janssen, "Blockchain in government: Benefits and implications of distributed ledger technology for information sharing," *Government Information Quarterly*. 2017, doi: 10.1016/j.giq.2017.09.007.
[112] K. S. Hald and A. Kinra, "How the blockchain enables and constrains supply chain performance," *Int. J. Phys. Distrib. Logist. Manag.*, 2019, doi: 10.1108/IJPDLM-02-2019-0063.
[113] I. Kothman and N. Faber, "How 3D printing technology changes the rules of the game," *J. Manuf. Technol. Manag.*, 2016, doi: 10.1108/jmtm-01-2016-0010.
[114] A. Laplume, G. C. Anzalone, and J. M. Pearce, "Open-source, self-replicating 3-D printer factory for small-business manufacturing," *Int. J. Adv. Manuf. Technol.*, 2016, doi: 10.1007/s00170-015-7970-9.
[115] J. H. Cheng and K. L. Lu, "Enhancing effects of supply chain resilience: insights from trajectory and resource-based perspectives," *Supply Chain Manag.*, 2017, doi: 10.1108/SCM-06-2016-0190.
[116] M. Kamalahmadi and M. Mellat-Parast, "Developing a resilient supply chain through supplier flexibility and reliability assessment," 2016, doi: 10.1080/00207543.2015.1088971.
[117] T. J. Pettit, K. L. Croxton, and J. Fiksel, "The Evolution of Resilience in Supply Chain Management: A Retrospective on Ensuring Supply Chain Resilience," 2019, doi: 10.1111/jbl.12202.
[118] J. Fiksel, M. Polyviou, K. L. Croxton, and T. J. Pettit, "From risk to resilience: Learning to deal with disruption," *MIT Sloan Manag. Rev.*, 2015.
[119] A. A. Emelogu, "Optimal supply chain configuration for the additive manufacturing of biomedical implants," *ProQuest Diss. Theses*, 2016.
[120] K. Oettmeier and E. Hofmann, "Impact of additive manufacturing technology adoption on supply chain management processes and components," *J. Manuf. Technol. Manag.*, 2016, doi: 10.1108/JMTM-12-2015-0113.
[121] P. Tatham, J. Loy, and U. Peretti, "Three dimensional printing – a key tool for the humanitarian logistician?," *J. Humanit. Logist. Supply Chain Manag.*, 2015, doi: 10.1108/JHLSCM-01-2014-0006.
[122] J. M. Pearce, "Distributed manufacturing of open source medical hardware for pandemics," *Journal of Manufacturing and Materials Processing*. 2020, doi: 10.3390/jmmp4020049.
[123] A. V. Thomas and B. Mahanty, "Interrelationship among resilience, robustness, and bullwhip effect in an inventory and order based production control system," *Kybernetes*, 2019, doi: 10.1108/K-11-2018-0588.
[124] D. Marks and E. Elinoff, "Splintering disaster: relocating harm and remaking nature after the 2011 floods in Bangkok," *Int. Dev. Plan. Rev.*, 2019, doi: 10.3828/idpr.2019.7.
[125] K. Das, "Integrating resilience in a supply chain planning model," *Int. J. Qual. Reliab. Manag.*, 2018, doi: 10.1108/IJQRM-08-2016-0136.
[126] L. Sun and L. Zhao, "Envisioning the era of 3D printing: a conceptual model for the fashion industry," *Fash. Text.*, 2017, doi: 10.1186/s40691-017-0110-4.
[127] Y. Liu, J. S. Srai, and S. Evans, "Environmental management: the role of supply chain capabilities in the auto sector," *Supply Chain Manag. An Int. J.*, vol. 21, no. 1, pp. 1–19, Jan. 2016, doi: 10.1108/SCM-01-2015-0026.
[128] T. Gulledge and T. Chavusholu, "Automating the construction of supply chain key performance indicators," *Ind. Manag. Data Syst.*, 2008, doi: 10.1108/02635570810883996.