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Supply Chain Disruptions and Resilience in Manufacturing Industry During Covid-19: Additive Manufacturing Intervention in Perspective

Thywill Cephas Dzogbewu[1], Sampson Afrifa Jnr[1], Nathaniel Amoah[2], Samuel Koranteng-Fianko[1], Adam Imdaadulah[1], Deon Johan de Beer[1]

[1]Central University of Technology, Free State (South Africa)
[2]Universita degli Studi di Brescia (Italy)

thydzo@yahoo.fr, profafrifa21@gmail.com, nathanielamoah20@gmail.com, agapesam4@gmail.com, iadam@cut.ac.za, ddebeer@cut.ac.za

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Abstract:

Purpose: This paper examined supply chain disruptions in the manufacturing industry in South Africa and how additive manufacturing technology was used to help deal with disruptions encountered.

Design/methodology/approach: The study adopted a qualitative research approach in order to meet the objectives of the study. A total of ten (10) managers of conventional manufacturing firms and ten (10) managers of 3D printing firms in Free State, South Africa participated in the study through the use of a purposive sampling technique. Interview guides were used in the collection of data. Data transcriptions and thematic analysis were used to analyze data gathered from the interviews.

Findings: The results of the study showed that 3D printing contributed positively in dealing with manufacturing disruptions that were encountered by manufacturing firms in Free State, South Africa through the production of components and spare parts that were broken down in manufacturing machinery/plants. From the study, the researchers recommend that 3D printing technology should be adopted by manufacturing firms because of its practicality in providing manufacturing support and production continuity even in supply chain disruptive experiences caused by pandemics such as Covid-19.

Originality/value: The study proves that due to the versatility of the 3D printing technology it could be used to minimize the effect of supply chain disruption during cries such as the Covid-19 pandemic. One of the unique contributions of the current study is the realization that additive manufacturing was not of much relevance to the generic supply chain challenges encountered in supply chain activities, but rather very relevant in helping to prevent disruptions of the manufacturing process by improvising spare parts at the peak of the Covid-19 pandemic.

Keywords: supply chain, Covid-19, disruption, 3D printing, additive manufacturing, resilience

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1. Introduction

The current impact of Covid-19 on supply chains is very drastic (Khairallah, Anderson, Rubenchik & King, 2016). Covid-19 has adversely affected the manufacturing sector by causing supply chain disruptions in the activities of manufacturing firms (pwc, 2020). Manufacturing firms were negatively affected especially in terms of their production (Alkahtani, Omair, Khalid, Hussain, Ahmad & Pruncu, 2021). As a result of lockdowns and the closure of country borders, most manufacturing firms were entangled with the challenge of getting access to raw materials for production in real-time (Alkahtani et al., 2021). As raw materials were delayed, it brought about delays in the entire production process for manufacturing firms (Kapparashetty, 2020). Apart from the production delays, the lack of accessibility to raw materials for manufacturing firms also contributed to disruptions in the entire manufacturing process which therefore made it difficult for most manufacturing firms to meet the needs of their customers (Kapparashetty, 2020).

Another challenge that was encountered by manufacturing firms is the increased production costs (Butt, 2021). The increased production cost was a result of shortages in raw materials for production. This is because shortages in raw materials brought about increases in the prices of raw materials. As a result of lockdowns and closure of borders in most countries, some manufacturing firms had to find other alternatives for getting raw materials to their production sites at extra costs which also contributed to increased production costs (Butt, 2021; Kumar, Luthra, Mangla & Kazançoğlu, 2020). Another contributor to the increased production costs for manufacturing firms was the extra costs that they had to incur in ensuring that the raw materials used are properly sanitized to prevent any kind of infections (Rahman, Taghikhah, Paul, Shukla & Agarwal, 2021). Moreover, manufacturing firms had to incur extra costs in terms of ensuring that the production environment is safe by disinfecting production machinery on regular basis, providing employees with Personal Protective Equipment (PPEs), and also creating avenues for Covid-19 protocols to be duly observed during the production process (Rahman et al., 2021; Aday & Aday, 2020).

In some circumstances, some manufacturing firms had to invest in robotic technology and artificial intelligence in order to reduce the level of human-to-human interactions during the production processes and all of these came at extra costs, thereby increasing the overall production costs of manufacturing firms (Wang & Wang, 2021). The Covid-19 pandemic also brought about disruptions in the production processes of most manufacturing firms due to the breakdown of machinery and the inability of manufacturing firms to import spare parts from their original suppliers (Rapaccini, Saccani, Kowalkowski, Paiola & Adrodegari, 2020). Breakdown in machinery and the unavailability of spare parts to continue the manufacturing process further led to low productivity of manufacturing firms and also a decrease in the speed of production of final products to the end users (Aday & Aday, 2020; Rapaccini et al., 2020).

Additionally, Alkahtani et al., (2021) found a decrease in labor supply, an increase in the risk premium, and an increase in production costs in all sectors as supply-side impacts of the Covid -19 pandemic. Covid-19 has had a major impact on the management of global value chains. The introduction of tighter export restrictions by some major economies that are experiencing a shortage has also contributed to the rise in prices (Kapparashetty, 2020; Kapoor, Bigdeli, Dwivedi & Raman, 2021).

Due to the fact that the Covid-19 pandemic made it difficult for manufacturing firms to have access to raw materials due to travel and border restrictions, it was important for them to devise an alternative means of having access to these raw materials (UNCTAD, 2020a). Since there were intense difficulties in sourcing raw materials from foreign suppliers, some manufacturing firms had to rather source their raw materials from local suppliers (Butt, 2021; UNCTAD, 2020b). Sourcing raw materials from local suppliers helped some manufacturing firms to have access to raw materials in real time to prevent delays in their production processes and also save costs associated with the non-accessibility of raw materials for production purposes (Butt, 2021; International Labor Organization, 2020). Sourcing from local suppliers helps manufacturing firms to reduce three types of costs. First, it helps manufacturing firms to reduce transportation costs associated with sourcing their raw materials from foreign suppliers. Second, manufacturing firms also save costs associated with the storage of raw materials that will spend longer days/months at the ports due to the restrictions at the borders. Third, manufacturing firms save costs associated with delays in production due to delays in accessibility of raw materials that have a negative impact on their productivity and profitability (Rapaccini et al., 2020; Nicola, Alsafi, Sohrabi, Kerwan, Al-Jabir, Iosifidis et al., 2020).

Product diversification was also a key response to help manufacturing firms to deal with their production challenges during the Covid-19 pandemic (Fisher-Ke, Otto & Han, 2022; Attah, 2021). Product diversification became important due to the demand uncertainty for most manufacturing firms. This is because, as people were constantly focused on following safety protocols to help them stay healthy and refrain from contracting the Covid-19 virus, it became extremely difficult for manufacturing firms to produce to meet the demand of consumers (Fisher-Ke et al., 2022). In order for some manufacturing firms to survive, they had to develop the capacity to produce products that were in high demand, especially at the peak of the Covid-19 pandemic such as nose masks, face shields, hand sanitizers, and other PPEs that could be used by people to prevent themselves from contracting the Covid-19 virus (Fisher-Ke et al., 2022; Harapko, 2021). As part of the product diversification strategy, most manufacturing firms adopted the differentiation strategy by producing different types of safety kits and PPEs for the new market of consumers who were eager to protect themselves from contracting the Covid-19 pandemic (Lin, Fan, Shi & Fu, 2021). Apart from manufacturing firms diversifying their products to help mitigate the Covid-19 pandemic, some of these manufacturing firms drastically reduced the prices of these PPEs to make them more affordable to the ordinary person to afford, thereby adopting the cost leadership strategy. Some of the manufacturing firms also adopted the focus strategy by giving credence to specific geographical locations where the Covid-19 pandemic had been at its highest peak (Lin et al., 2021; Nkhata & Mwenifumbo, 2020).

The adoption of Additive Manufacturing (AM) which is colloquially known as 3D printing technology also became one of the strategies used by manufacturing firms to deal with supply chain disruptions in their production processes as a result of the Covid-19 pandemic (Dzogbewu, Jnr, Amoah, Fianko & de Beer, 2021). Additive manufacturing is a layer-by-layer method of producing three-dimensional (3D) structures (Dzogbewu & du Preez, 2022). It is considered a renaissance of the manufacturing industry and has the capability of manufacturing 3D structures with tailored geometrical configurations for a particular industrial application (Arora, Arora, Kumar & Pant, 2020).

3D printing technology is said to have a competitive advantage compared to classical manufacturing methods due to its layer-wise manufacturing strategy (Dzogbewu, Amoah, Fianko, Afrifa & de Beer, 2022). The layer-wise manufacturing process based on a 3D CAD (Computer-aided design) model permits the addition of material to produce 3D structures instead of removing waste material in different steps as used by the conventional methods of manufacturing (Dzogbewu et al., 2021). The additive manufacturing or 3D printing technology process is considered an eco-design topology optimization process of manufacturing near-net-shapes that eliminate the assembling steps of components, avoid waste of manufacturing materials, reduce the time spent on manufacturing, improve performance reliability, promote weight reduction, and less fuel consumption leading to sustainable development at a lower cost (Dzogbewu, Monaheng, Yadroitsava, Du Preez & Yadroitsev, 2017).

The agility of additive manufacturing technology becomes more pronounced during the zenith of the Covid-19 pandemic (Dzogbewu et al., 2021). The current research would therefore examine its resilience in the manufacturing industry in the Free state province of South Africa. This is because South Africa is the leading additive manufacturing country on the African continent and the Free state province is known as the additive manufacturing hub; due to the intense ongoing research and commercial production of 3D components for various industrial applications in the province (CRPM, 2021; CSIR, 2020).

2. Supply Chain Resilience and Additive Manufacturing Technology

Supply chain resilience is the ability of a firm to bounce back from disruptive situations. More specifically, supply chain resilience characterizes the systems' adaptive capability to tolerate temporary disruptive events (Belhadi, Kamble, Venkatesh, Chiappetta-Jabbour & Benkhati, 2022; Mckinnon, 2020). Prior studies pointed out that in the case of alternative suppliers, design information substitutability and portability were required by firms to improve supply chain resilience capability (Belhadi et al., 2022). From the organizational perspective, supply chain resilience is defined as the organizational capacity or ability to facilitate available operational resources to cope with internal and external shocks (Spieske & Birkel, 2021; Dominic-Essuman, Boso & Annan, 2020). Thus, supply chain resilience refers to the behavioral responses of firms, national economies, and systems in the contexts of social and economic risk events such as pandemics (Spieske & Birkel, 2021). As a part of a business continuity strategy, supply chain resilience prepares firms with the capacity to cope with and recover from disruptions to the original state of operations (Ali, Suleiman, Khalid, Tan, Tseng & Kumar, 2021). It reflects an organization's ability to survive, adapt, respond, recover, and grow when confronted with change and uncertainty in the business environment (Ali et al., 2021; Pereira, Christopher & Lago da Silva, 2014). Researchers also view supply chain resilience as a dynamic capability when founded on the ability to manage disruptions and events to increase the speed of recovery to its original state (Ozdemir, Sharma, Dhir & Daim, 2022).

Additive manufacturing (AM) technology was more resilient in a situation like the Covid-19 pandemic (Spieske & Birkel, 2021). This is because, despite lockdowns and travel bans, employees from AM firms could still design objects for their customers and share such designs using cloud platforms and then get them printed in their floor factories in real-time (Spieske & Birkel, 2021). As the Covid-19 pandemic became more severe and shortages in medical supplies became a key problem to deal with, the 3D printing firms as a result of the 3D technology engaged in the design of medical goggles, face masks, medical ventilator valves, breathing masks, among others which were later printed using 3D printing machines as a way of helping to deal with the control of the Covid-19 pandemic (Dzogbewu et al., 2021). The digital capacity of 3D printing technology makes it a key advantage over traditional manufacturing which relies on employees and raw materials which are supposed to be processed in production plants before finished goods can be transported to end users (Dzogbewu et al., 2021).

The short manufacturing time that the AM technology takes to come out with finished products also provides a key supply chain resilient feature in circumstances such as the Covid-19 pandemic (Ambrogio, Filice, Longo & Padovano, 2022). The final manufacturing time for AM products takes a few days to complete (Ambrogio et al., 2022). The AM manufacturing process provides the opportunity of preparing even the most non-standard and hardly available custom-made elements in a short time. AM technology allows parts to be made where and when they are required, without very expensive moulds (Dzogbewu, 2020).

Decentralized manufacturing is another useful supply chain resilient feature of the AM technology (Basu, Abdulrahman & Yuvaraj, 2022). This is because, when AM entities share digital models over the internet, it creates an international Internet of Things (IoT) for 3D manufacturing that breaks down geographical barriers and enables local production in real-time (Basu et al., 2022). Furthermore, improving production efficiency is made possible by the cloud manufacturing platform. There are many other digital models of personal protective equipment (PPE) available as a result of using 3D printing technology (Basu et al., 2022).

The AM manufacturing strategy also helps to maintain continuity in production and this may occur in the case the supplier of a part fails (Belhadi et al., 2022). Such a situation exposes companies to financial losses which may grow with time, when awaiting a replacement. Finding a new local supplier, in a crisis situation, can be a big challenge (Dartnell & Kish, 2021). Therefore, AM was used to produce spare parts to ensure continuity in production. This reduces downtime due to missing parts. Owing an AM machine is a perfect alternative for fast access to spare parts needed for the operation of a given device or the whole engineering line (Dartnell & Kish, 2021).

Many components used in machines and devices can be replaced by 3D-printed parts. The use of high-performance 3D printing materials such as PEEK, ULTEM, or PC allows the manufacturing of parts that have very good mechanical properties (Profili, Brunet, Dubois, Groenhuis & Hof, 2021). Parts from these filaments can be chosen as metal parts replacement. In case the supplier of spare parts runs out of stock, 3D printers can be used to produce customized spare parts for organizations to use (Bezek, Pan, Harb, Zawaski, Molla, Kubalak et al., 2021).

3. Methodology

This study adopted the qualitative research design. The choice of the qualitative research design was justified on the premise that the researchers sought to gain an in-depth understanding of how 3D printing technology helped manufacturing firms to build supply chain resilience as a result of supply chain disruptions that affected the production process of manufacturing firms in South Africa during the peak times of the Covid-19 pandemic. The population of the study comprised both 3D printing firms and conventional manufacturing firms located in Free State, South Africa. Due to the qualitative nature of the study, the researchers selected managers of ten (10) 3D printing firms and also managers of ten (10) conventional manufacturing firms in Free State, South Africa. The total sample size for the study was therefore twenty (20) participants from both 3D printing firms and conventional manufacturing firms located in Free State. Structured interviews served as the data collection instrument. The structured interviews were designed with the motive of achieving the objectives of the study. Data gathered from the structured interviews were analyzed through data transcriptions and identification of themes.

4. Results

According to the result from table 1, majority of the respondents were males as they constituted 70% while females constituted 30%. Regarding the age of respondents, it was found that most of the respondents were between the ages of 25-35 years as they constituted 40%, 25% were between the ages of 35-45 years, 20% of the respondents were less than 25 years while 15% of the respondents were more than 45 years. Regarding the educational level of respondents, it was found that 75% have attained their first degree, while 25% have attained their masters' degree. In terms of industry type, 50% of respondents are from 3D printing firms while another 50% are also from manufacturing firms in Free State, South Africa.

Gender	Frequency	Percentage (%)
Male	14	70
Female	6	30
Total	20	100
Age	**Frequency**	**Percentage (%)**
Less than 25 years	4	20
25-35 years	8	40
35-45 years	5	25
More than 45 years	3	15
Total	20	100
Educational Level	**Age**	**Frequency**
First Degree	15	75
Masters/Postgraduate	5	25
Total	20	100
Industry type	**Age**	**Frequency**
3D printing firm	10	50
Manufacturing firm	10	50
Total	20	100

Table 1. Demographic Data of respondents

4.1. How 3D Printing Helped Solve the Problem of Production Disruptions During the Covid-19 Pandemic

The following themes were identified by the researchers based on the responses on the subject matter of how 3D printing technology helped to solve the problem of disruptions in the production process of manufacturing firms during the peak times of the Covid-19 pandemic in South Africa.

4.1.1. Production of Components and Spare Parts

According to the respondents, the adoption of 3D printing technology by manufacturing firms in Free State, South Africa enhanced continuity of the manufacturing process. The respondents explained that, during the peak times of the Covid-19 pandemic, it was impossible to import original components and spare parts of manufacturing plants/machinery used in the production process and so 3D technology was able to support them accordingly in that regard. Respondents were quoted in this manner:

"The Covid-19 really disrupted the manufacturing process. However, by the nature of 3D printing technology it came in handy. We were able to produce components and spare parts that we need to keep our manufacturing process ongoing".

"The lockdowns made it impossible at the time for us to contact our main suppliers to ship the spare parts of the broken machinery to us, so we had to quickly get 3D experts to come in and they really helped us to get the spare parts and by that production continued".

"I would say that, without 3D printing we will be out of business. It was very frustrating for us at the peak times of the Covid-19 pandemic to produce some of the PPEs to help support the fight against Covid-19. With the breakdown of key parts of our machinery that was impossible. I was impressed with 3D technology because the CAD designers produced wonderful designs and we had the option to choose what we wanted and that really helped to get our business back on track".

"I will say that without 3D printing technology, most manufacturing firms in Free State South Africa would have collapsed because there was excessive pressure on our machinery which led to a lot of breakdowns here and there. However, the 3D technology came to solve a major problem for all of us by helping to get 3D printed spare parts that fit into our machinery to enhance production".

4.1.2. Rapid Adoption of Hybrid Technology

From the responses that were given, the researchers inferred that although conventional manufacturing is still being used by most manufacturing firms, the disruptions in the manufacturing process due to the breaking down of parts of manufacturing plants that could not be replaced through imports from the original sources, compelled most manufacturing firms to adopt a hybrid technology rapidly. Thus, by the hybrid technology, manufacturing firms combined their conventional manufacturing with 3D printing technology in order to have the capacity to produce and replace spare parts for machinery especially in the train industry and mining industries in Free State, South Africa. Respondents explained as follows:

"In Free State, institutions such as Centre for Rapid Prototyping and Manufacturing (CRPM) collaborated with Center of Scientific and Industrial Research (CSIR) to use hybrid technology to provide components/spare parts for broken down parts of machinery and manufacturing plants for a lot of manufacturing companies in order to keep their production processes ongoing since it was impossible for these manufacturing firms to get the original spare parts through importation as a result of the travel restrictions during the peak times of the Covid-19 pandemic".

"I must say that the adoption of hybrid technology among manufacturing firms in Free State became so important because changing the entire manufacturing process to 3D printing technology alone was going to be very difficult for a lot of the manufacturing firms because of the technicalities involved and also the cost implications. The hybrid technology therefore served a good purpose of enhancing efficient manufacturing processes in such a critical time like the Covid-19 pandemic".

"In our case, we really had no option but to integrate the 3D technology into our conventional manufacturing process. This is because, the 3D printing technology helped us to maintain our machinery by printing spare parts for us in real-time while continually going by our conventional manufacturing for the production of products for our clients".

"I think that, we did not really have the time to change our entire manufacturing process to 3D printing technology and so we thought of hybrid technology in other for us to harness the benefits associated with the 3D printing technology. In fact, the adoption of the hybrid technology even helped us to produce PPEs to support most hospitals in Free State as our contribution to the fight against Covid-19 in South Africa".

Figure 1 shows some of the tooling components which was produced using both additive manufacturing and conventional manufacturing techniques. These components were used to produce PPE during the Covid-19 pandemic. The PPE was intended for use by medical personnel who were on the front lines fighting the pandemic in Free State, South Africa. Figure 2 shows a 3D printed tooling insert as placed inside a conventionally machined tooling bolster. These components were used to injection mould to produce some of the PPE components.

Figure 1. Hybrid tooling used for the production of PPE during the Covid19 pandemic (courtesy Advanced Manufacturing Unit: PDTS). A: 3D Printed tooling insert. B: Conventionally machined tooling component

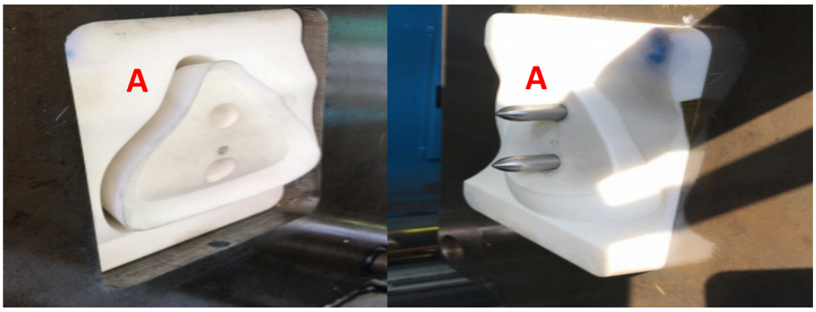

Figure 2. 3D printed tooling inserts (A) inside a conventionally machined tooling bolster (courtesy Advanced Manufacturing Unit: PDTS)

4.1.3. Flexibility in Manufacturing Process

From the responses, it could be deduced that 3D printing technology helped to make the production process of manufacturing firms more flexible due to the support it provided in producing spare parts for broken down parts of manufacturing machinery/plants during the peak times of the Covid-19 pandemic. The respondents further explained that the ease of use of the CAD model, made it possible for 3D printing technology to produce even complex spare parts with ease to support the production process of manufacturing firms in Free State, South Africa. Some respondents were quoted in this manner:

"By the very nature of 3d printing, it is more flexible technology as compared to most conventional technology. Due to the use of the CAD model, it can be used to produce complex components with ease. It is tailored technology that can help to produce any shape with ease without a complex tooling process as in conventional manufacturing methods. There is normally no major post-processing process as in the conventional methods which makes the 3D printing technology more flexible and easier to use technology".

"The 3d printing technology was used to ensure the production of most manufacturing firms did not come to a halt. Components that were breakdown and could not be procured outside the country were produced using 3D printing or a hybrid manufacturing process. The 3D printing really makes it possible for most mining companies to remain in business since almost every broken-down component could be produced immediately. In some cases, CAD files of broken parts spare parts were sent via the internet to be printed by a 3D company for a conventional manufacturing company to continue with their manufacturing process".

"The very nature of 3D printing is flexible; in that it allows for many different iterations of a single part to be produced at once. Resulting in production companies being able to analyze and compare product iterations in a very short space of time".

"In terms of hybrid manufacturing, 3D printing has really proven to be versatile in that 3D printed components can seamlessly be introduced into a manufacturing space".

5. Discussion of Findings

This section discussed the results of the study by linking it up with relevant literature. From the results of the study, 3D printing contributed positively in dealing with manufacturing disruptions that were encountered by manufacturing firms in Free State, South Africa through the production of components and spare parts that were broken down in manufacturing machinery/plants, rapid adoption of hybrid technology and also ensuring flexibility in the manufacturing process. The findings of this study were unique when compared to the literature. This is because the literature on supply chain resilience strategies focused more on the benefits of 3D technology to 3D printing firms and not necessarily the interventions provided by 3D printing firms to deal with disruptions encountered in the production processes of manufacturing firms.

For instance, literature stipulated that 3D printing technology enabled CAD designers of 3D printing firms to design objects for clients and use cloud platforms to send their designs to 3D factories in real-time (Spieske & Birkel, 2021). Again, the literature also talked about the efficiency of 3D printing technology in producing finished goods in real-time. For example, according to Dzogbewu et al. (2022), the final manufacturing time for 3D printing products takes a few days to complete with daily capacities of over one hundred. 3D printers provide the opportunity of preparing even the most non-standard and hardly available custom-made elements in a short time. Furthermore, literature talked about decentralized manufacturing as a supply chain resilient feature of 3D printing technology. This is because, when 3D printing entities share digital models over the internet, it creates an international Internet of things (IoT) for 3D manufacturing that breaks down geographical barriers and enables local production in real-time (Ambrogio, 2022). Furthermore, improving production efficiency is made possible by the cloud manufacturing platform.

The aspect of the study which was in congruence with the literature was the use of 3D technology to help in maintaining continuity in production through the production of spare parts for manufacturing firms. The literature explained that the failure of suppliers outside the country to provide spare parts to manufacturing firms can have financial implications on their production process and also the difficulty in finding a local supplier of the spare parts makes the adoption of 3D printing technology a good measure to ensure continuity in the production process. Many components used in machines and devices can be replaced by 3D-printed parts. The use of high-performance 3D printing materials such as PEEK, ULTEM, or PC made it possible to manufacture parts with that have very good mechanical properties (Profili et al, 2021). What is more, parts from these filaments can be chosen as metal parts replacement. In case the supplier of spare parts runs out of stock, 3D printers can be used to produce customized spare parts for organizations to use (Bezek et al., 2021). This study, therefore, remains unique in its findings because it found two interventions that are different from what exists in literature which are the rapid adoption of hybrid technology and also flexibility in the production process as a result of adopting 3D printing technology.

6. Implications

The study was conducted to assess the role of 3D printing in dealing with supply chain disruptions encountered by manufacturing firms in Free State, South Africa as a result of the Covid-19 pandemic. From the study, it could be deduced that 3D printing was not of much relevance to the generic supply chain challenges encountered in supply chain activities of manufacturing firms such as the difficulties in having access to raw materials. Rather, 3D printing technology was most relevant in helping to deal with production disruptions that were encountered by manufacturing firms during the Covid-19 pandemic as a result of breakdowns of components of manufacturing machinery/plants. The study also deduced that, apart from the use of 3D printing technology in producing spare parts for manufacturing machinery/plants, it also contributed to the adoption of hybrid technology (combination of 3D printing and conventional manufacturing technology) to enhance production continuity among various manufacturing firms, especially in the train and mining firms. Also ensuring flexibility in the manufacturing process is another intervention worth noting in the adoption of 3D printing technology among manufacturing firms during the peak times of the Covid-19 pandemic.

From the study, the researchers recommend that 3D printing technology should be adopted by manufacturing firms because of its practicality in providing manufacturing support and production continuity even in supply chain disruptive experiences caused by pandemics such as Covid-19.

The study also recommends the need for managers and owners of manufacturing firms to get the expertise to help them integrate 3D printing technology with their conventional manufacturing technology to enhance production continuity even amidst disruptive circumstances such as the Covid-19 pandemic.

The study recommends the need for future researchers to explore further to understand the factors that influence the decisions of owners and managers of manufacturing firms in their adoption of 3D printing technology alone or hybrid technology in the provision of spare parts for broken components of manufacturing machinery/plants.

7. Conclusions

This study examined supply chain disruptions in the manufacturing industry in South Africa and the role played by 3D printing technology in dealing with the disruptions identified. Based on the findings of the study, the researchers conclude that 3D printing technology positively intervened in the production process of manufacturing firms in the Free State, South Africa. The adoption of the hybrid technology which combined both 3D printing with conventional manufacturing was also appropriate for ensuring that malfunctioning machinery were replaced with customized spare parts through 3D printing technology and also hybrid technology. Due to the agility provided by AM manufacturing process, manufacturing firms that responded to the challenge posed by the Covid-19 pandemic were able to stay afloat during the pandemic and serve its ice hands.

Declaration of Conflicting Interests

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References

Aday, S., & Aday, M.S. (2020). Impact of COVID-19 on the food supply chain. *Food Quality and Safety,* 4(4), 167-180. Oxford Academic. https://doi.org/10.1093/fqsafe/fyaa024

Ali, M.H., Suleiman, N., Khalid, N., Tan, K.H., Tseng, M.L., & Kumar, M. (2021). Supply chain resilience reactive strategies for food SMEs in coping to COVID-19 crisis. *Trends in Food Science & Technology*, 109, 94-102. https://doi.org/10.1016/j.tifs.2021.01.021

Alkahtani, M., Omair, M., Khalid, Q.S., Hussain, G., Ahmad, I., & Pruncu, C. (2021). A COVID-19 Supply Chain Management Strategy Based on Variable Production under Uncertain Environment Conditions. *International Journal of Environmental Research and Public Health*, 18(4), 1662. https://doi.org/10.3390/ijerph18041662

Ambrogio, G., Filice, L., Longo, F., & Padovano, A. (2022). Workforce and supply chain disruption as a digital and technological innovation opportunity for resilient manufacturing systems in the COVID-19 pandemic. *Computers & Industrial Engineering*, 169, 108158. https://doi.org/10.1016/j.cie.2022.108158

Arora, R., Arora, P.K., Kumar, H., & Pant, M. (2020). Additive Manufacturing Enabled Supply Chain in Combating COVID-19. *Journal of Industrial Integration and Management,* 5(4), 495-505. https://doi.org/10.1142/S2424862220500244

Attah, A.N. (2021). Initial Assessment of the Impact of COVID-19 on Sustainable Forest Management African States Alhassan Nantogmah Attah Background Paper prepared for the United Nations Forum on Forests Secretariat. *United Nations Forum on Forests Secretariat*. Available at: https://www.un.org/esa/forests/wp-content/uploads/2021/01/Covid-19-SFM-impact-Africa.pdf

Basu, R.J., Abdulrahman, M.D., & Yuvaraj, M. (2022). Improving agility and resilience of automotive spares supply chain: The additive manufacturing enabled truck model. *Socio-Economic Planning Sciences*, 85, 101401. https://doi.org/10.1016/j.seps.2022.101401

Belhadi, A., Kamble, S.S., Venkatesh, M., Chiappetta-Jabbour, C.J., & Benkhati, I. (2022). Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view. *International Journal of Production Economics*, 249, 108516. https://doi.org/10.1016/j.ijpe.2022.108516

Bezek, L.B., Pan, J., Harb, C., Zawaski, C.E., Molla, B., Kubalak, J.R. et al. (2021). Additively manufactured respirators: quantifying particle transmission and identifying system-level challenges for improving filtration efficiency. *Journal of Manufacturing Systems*, 60, 762-773. https://doi.org/10.1016/j.jmsy.2021.01.002

Butt, A.S. (2021). Understanding the implications of pandemic outbreaks on supply chains: an exploratory study of the effects caused by the COVID-19 across four South Asian countries and steps taken by firms to address the disruptions. *International Journal of Physical Distribution & Logistics Management*, 52(4), 370-392. https://doi.org/10.1108/IJPDLM-08-2020-0281

CRPM (2021). *The CRPM leads South Africa in Additive Manufacturing techniques, innovations and solutions*. Available at: https://news.knowledia.com/ZA/en/articles/the-crpm-leads-south-africa-in-additive-manufacturing-techniques-e825552ec71af73570641c9198893eb02a34a1fb

CSIR (2020). *CSIR and TIA join forces to support SMMEs in the fight against COVID-19 using Television White Spaces Technology | CSIR*. Available at: https://www.tia.org.za/blog/2020/05/04/csir-and-tia-join-forces-to-support-smmes-to-covid-19/

Dartnell, L.R., & Kish, K. (2021). Do responses to the COVID-19 pandemic anticipate a long-lasting shift towards peer-to-peer production or degrowth? *Sustainable Production and Consumption*, 27, 2165-2177. https://doi.org/10.1016/j.spc.2021.05.018

Dominic-Essuman, A., Boso, N., & Annan, J. (2020). *Operational resilience, disruption, and efficiency: Conceptual and empirical analyses.* Available at: https://repository.up.ac.za/bitstream/handle/2263/75472/Essuman_Operational_2020.pdf?sequence=1 https://doi.org/10.1016/j.ijpe.2020.107762

Dzogbewu, T.C. (2020). Laser powder bed fusion of Ti6Al4V lattice structures and their applications. *Journal of Metals, Materials and Minerals*, 30(4), 68-78. https://doi.org/10.55713/jmmm.v30i4.821

Dzogbewu, T.C., Amoah, N., Fianko, S.K., Afrifa, S., & de Beer, D. (2022). Additive manufacturing towards product production: A bibliometric analysis. *Manufacturing Review,* 9, 1. https://doi.org/10.1051/mfreview/2021032

Dzogbewu, T.C., & du Preez, W.B. (2022). Producing Ti5Mo-Fused Tracks and Layers via Laser Powder Bed Fusion. *Metals*, 12(6), 950. https://doi.org/10.3390/met12060950

Dzogbewu, T.C., Jnr, S.A., Amoah, N., Fianko, S. K., & de Beer, D. (2021). Additive Manufacturing Interventions during the COVID-19 Pandemic: South Africa. *Applied Sciences 2022,* 12(1), 295. https://doi.org/10.3390/APP12010295

Dzogbewu, T.C., Monaheng, L, Yadroitsava, I., Du Preez, W.B., & Yadroitsev, I. (2017). Finite Element Analysis in Design of DMLS Mandible Implants. Challenges for Technology Innovation: An Agenda for the Future. *Proceedings of the International Conference on Sustainable Smart Manufacturing, S2M 2016. CRC Press/Balkema*. https://doi.org/10.1201/9781315198101-33

Fisher-Ke, J., Otto, J., & Han, C. (2022). Customer-Country diversification and inventory efficiency: Comparative evidence from the manufacturing sector during the pre-pandemic and the COVID-19 pandemic periods. *Journal of Business Research*, 148, 292-303. https://doi.org/10.1016/j.jbusres.2022.04.066

Harapko, S. (2021). *How COVID-19 impacted supply chains and what comes next*. Ernst & Young LLP (EY US) Article. Available at: https://www.ey.com/en_za/supply-chain/how-covid-19-impacted-supply-chains-and-what-comes-next

International Labor Organization (2020). The impact of the COVID-19 pandemic on jobs and incomes in G20 economies. *ILO-OECD Paper Prepared at the Request of G20 Leaders Saudi Arabia's G20 Presidency 2020*.

Kapoor, K., Bigdeli, A.Z., Dwivedi, Y.K., & Raman, R. (2021). How is COVID-19 altering the manufacturing landscape? A literature review of imminent challenges and management interventions. *Annals of Operations Research*, 1-33. https://doi.org/10.1007/s10479-021-04397-2

Kapparashetty, D.B.V. (2020). Impact of Covid 19 on Industrial Sector – A Study. *International Journal of Research and Analytical Reviews,* 7(1), 8.

Khairallah, S.A., Anderson, A.T., Rubenchik, A., & King, W.E. (2016). Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones. *Acta Materialia*, 108, 36-45. https://doi.org/10.1016/j.actamat.2016.02.014

Kumar, A., Luthra, S., Mangla, S.K., & Kazançoğlu, Y. (2020). COVID-19 impact on sustainable production and operations management. *Sustainable Operations and Computers*, 1, 1-7. https://doi.org/10.1016/j.susoc.2020.06.001

Lin, Y., Fan, D., Shi, X., & Fu, M. (2021). The effects of supply chain diversification during the COVID-19 crisis: Evidence from Chinese manufacturers. *Transportation Research Part E: Logistics and Transportation Review*, 155, 102493. https://doi.org/10.1016/j.tre.2021.102493

Mckinnon, A. (2020). *Building Supply Chain Resilience: a Review of Challenges and Strategies*. Available at: www.internationaltransportforum.org/jtrc/DiscussionPapers/jtrcpapers.html (Accessed: September 2022).

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C. et al. (2020). The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery,* 78, 185-193. https://doi.org/10.1016/j.ijsu.2020.04.018

Nkhata, M.J., & Mwenifumbo, A.W. (2020). Livelihoods and legal struggles amidst a pandemic: The human rights implications of the measures adopted to prevent, contain and manage covid-19 in Malawi. *African Human Rights Law Journal*, 20(2), 512-539. https://doi.org/10.17159/1996-2096/2020/v20n2a7

Ozdemir, D., Sharma, M., Dhir, A., & Daim, T. (2022). Supply chain resilience during the COVID-19 pandemic. *Technology in Society*, 68, 101847. https://doi.org/10.1016/j.techsoc.2021.101847

Pereira, C.R., Christopher, M., & Lago da Silva, A. (2014). Achieving supply chain resilience: the role of procurement. *Supply Chain Management*, 19(5/6), 626-642. https://doi.org/10.1108/SCM-09-2013-0346/FULL/XML

Profili, J., Brunet, R., Dubois, É.L., Groenhuis, V., & Hof, L.A. (2021). Use of 3D printed connectors to redesign full face snorkeling masks in the COVID-19 era: A preliminary technical case-study. *Annals of 3D Printed Medicine*, 3, 100023. https://doi.org/10.1016/j.stlm.2021.100023

pwc (2020). Impact of COVID-19 on the supply chain industry. *PricewaterhouseCoopers (Pwc)*, 1-16. Available at: http://www.pwc.com/ng/covid-19

Rahman, T., Taghikhah, F., Paul, S.K., Shukla, N., & Agarwal, R. (2021). An agent-based model for supply chain recovery in the wake of the COVID-19 pandemic. *Computers & Industrial Engineering*, 158, 107401. https://doi.org/10.1016/j.cie.2021.107401

Rapaccini, M., Saccani, N., Kowalkowski, C., Paiola, M., & Adrodegari, F. (2020). Navigating disruptive crises through service-led growth: The impact of COVID-19 on Italian manufacturing firms. *Industrial Marketing Management*, 88, 225-237. https://doi.org/10.1016/j.indmarman.2020.05.017

Spieske, A., & Birkel, H. (2021). Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic. *Computers & Industrial Engineering*, 158, 107452. https://doi.org/10.1016/j.cie.2021.107452

UNCTAD (2020a). *Assessing the Impact of COVID-19 on Africa's Economic Development.* Available at: https://airlines.iata.org/2020/03/09/potential-revenue-losses-113bn-due-covid-19-crisis (Accessed: September 2022).

UNCTAD (2020b). Impact of the COVID-19 pandemic on trade and development: Transitioning to a New Normal. *United Nations Conference on Trade and Development* (1-112). Available at: https://shop.un.org

Wang, X.V., & Wang, L. (2021). A literature survey of the robotic technologies during the COVID-19 pandemic. *Journal of Manufacturing Systems*, 60, 823-836. https://doi.org/10.1016/j.jmsy.2021.02.005