Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Review

The usefulness of additive manufacturing (AM) in COVID-19

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ABSTRACT

COVID-19 caused by novel coronavirus is a serious pandemic that has affected the various countries all across the globe. The effect of this pandemic is so devastating that many rising nations are brought to their knees and struggling to save the damage posed to their economy. Medical professionals and the healthcare community are paying their best effort to minimize and overcome the spread of this pandemic. To continue to fight against the COVID-19, healthcare delivery systems require the support of novel technologies which can meet their rapid demand for medical equipment and devices. The study explores the damage caused by COVID-19 to the industrial sector and the way AM is contributing to the economy post-COVID-19. State of the art concerning the application of AM in the present scenario especially to support the interrupted global supply chain is collected and analysed to identify its relevance in the battle against COVID-19.

1. Introduction

COVID-19 caused by novel coronavirus SARS-CoV2 (Severe acute respiratory syndrome-CoV2) first outbreak in Wuhan, China in December 2019 [1]. Before this, SARS-CoV was identified in 2003 in Guangdong, China which infected over 8000 people with more than 8% mortality rate [2]. COVID-19 is considered to be more brutal than SARS-CoV which initially began in selected regions of China but very soon spread to other countries and continents, and by March 2020 affected almost all places across the globe. Considering the significant impact of COVID-19 on our social lives, it was declared as a pandemic by the world health organization (WHO) [3]. Almost all the countries irrespective of their financial, medical, and social status suffered heavily in terms of economy, employment, education and loss of human lives. Despite the adoption of quarantine measures and complete lockdown, total confirmed cases were around 115 million with more than 2.50 million deaths globally till February 2021 [4]. A survey (Figs. 1 and 2) showed that 70% of total cases were only in eight major countries. Medical professionals, healthcare organizations, researchers and investigators all across the globe are continuously striving to slow down the effect of COVID-19 and develop the possible cure for this pandemic at the earliest. Artificial intelligence (AI) is proposed to be one of the techniques which (i) assists in tracing the spread of this virus, (ii) identifies the severity of disease and infected patients, and (iii) provides control over this infection in real-time [1,5–7]. However, to overcome the COVID-19 challenge, there is a need for a means by which the rapid requirement of a large demand for medical equipment, devices, isolation centres and other medical facilities can be satisfied. Moreover, to keep the economy moving, it is important to fabricate consolidated products with tailored properties involving minimum human to human interaction. The focus is on the processes that will help the industries to manage their uninterrupted supply chain system. Under these demanding constraints, additive manufacturing (AM) or 3D printing technologies emerge as a preferable solution.

AM is capable of rapid production of any complicated geometries with short product development time [8,9] with almost no human involvement. AM techniques provide customized products with complex geometries, less waste, and reduced time of product completion. AM application reduces the surplus expenditures in product development and can generate parts with high strength to weight ratio. AM is widely used in industrial applications including aerospace, automobile, construction, prototyping, and casting [10]. Ability to tackle variability, volume and delivery time constraints in the best possible manner, especially on-demand production scenario, makes this technology the best candidate to tackle the challenges emerged from the current scenario.

Many companies are using AM to produce replacement parts for medical ventilators, to develop face shields and face masks and other

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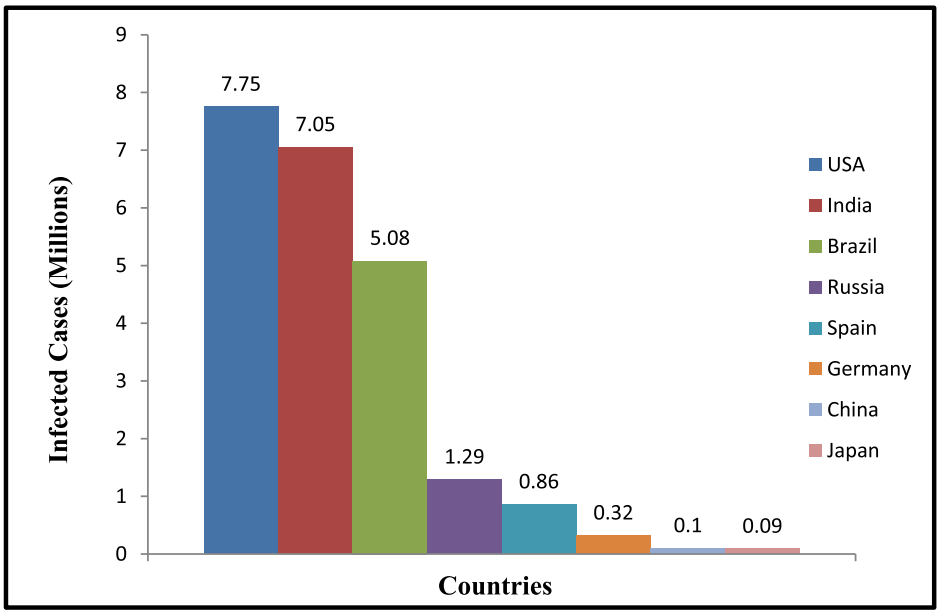

Fig. 1. COVID-19 infection rate in major countries [11].

healthcare facilities. Besides solving for direct medical needs, AM has also enabled manufacturers to develop hygiene and safety products like hands-free door handles and pedals. Present study reviews applications of AM in the time of COVID-19 and also explores possible application of AM and its driven technologies post COVID-19.

2. Materials and methods

Due to COVID-19, global industries and economy have been severely affected. Many industries went into lockdown mode and people were forced to work from their place owing to quarantine guidelines and shortage of personal protective equipment. Productivity has been severely affected and interruption in supply chain system has affected the economic growth. To analyze the impact of COVID-19 on industrial productivity and economy an extensive survey was made by collecting the data from various sources which included internet search, published articles, newspapers, magazines, manufacturing industries and experts. To summarize and analyze the collected data graphs were plotted and shown in next subsection. Based on the survey, possible application of AM in healthcare facilities, industries and global supply chain system has been explored.

2.1. Impact on industries and economy

COVID-19 is primarily a health and humanitarian crisis which has seriously affected human and their lives. In addition, global industries and the economy have also been affected badly. Many industries which were operating smoothly experienced unexpected loss or brought to shut down. In India lockdown put a lot of pressure on the industries and caused almost 20% of the GDP loss. An economic survey (Fig. 3) estimated that for 2017–2018 and 2018–2019 the growth rate was progressive and impressive. However, COVID-19

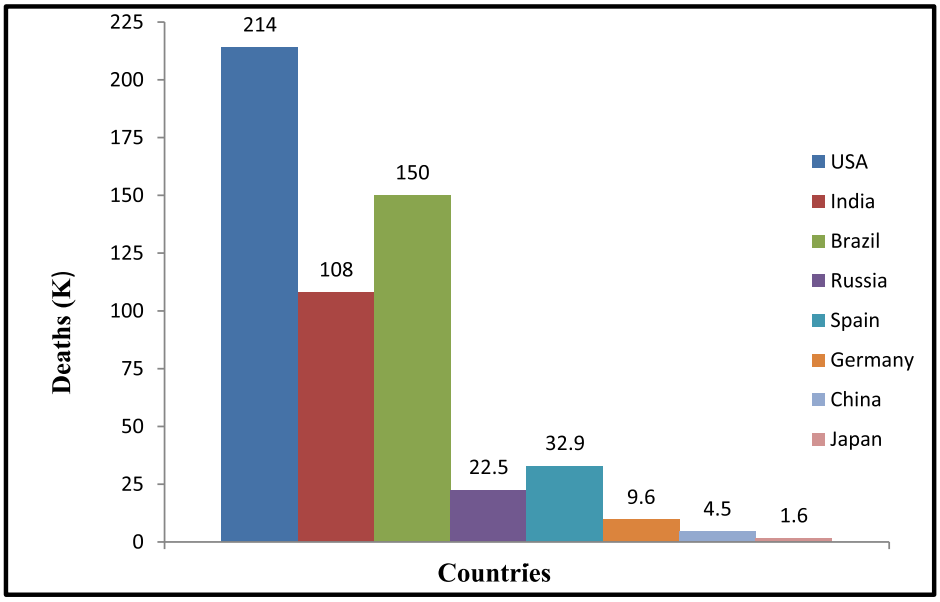

Fig. 2. COVID-19 deaths in major countries [11].

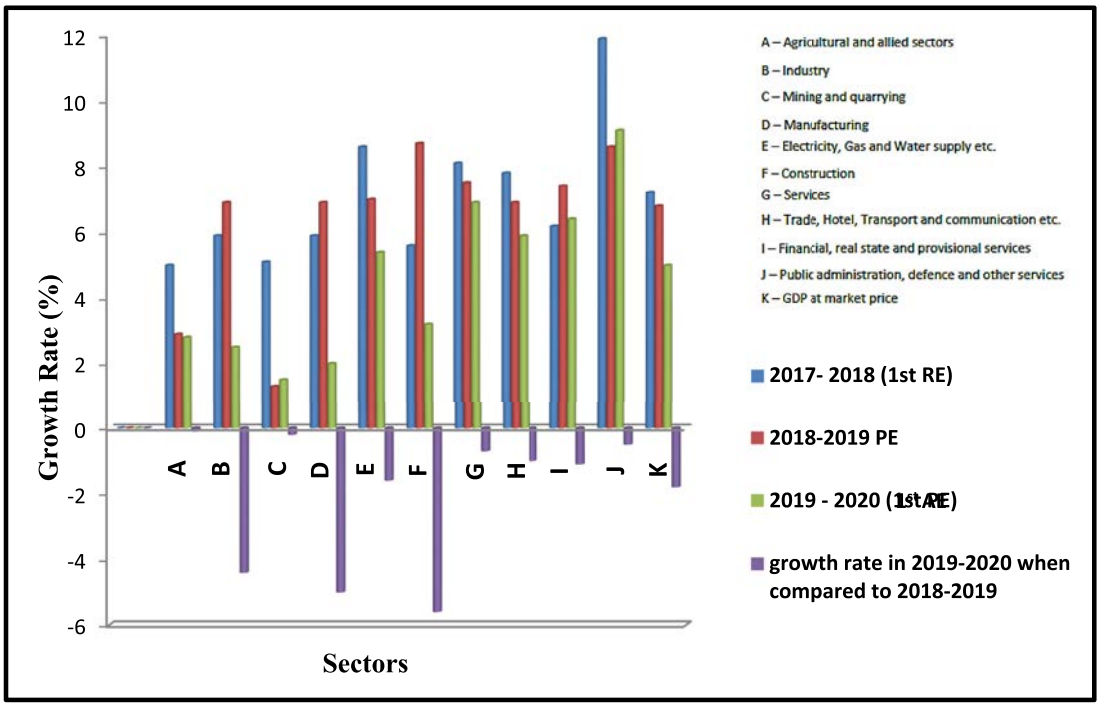

Fig. 3. GDP growth rate in India for 2019–2020 [15].

badly affected the majors sectors in the 1st AE (advanced estimates) of 2019–2020 and growth rate was severely decreased as compared to 2018–2019. Among all, the growth rate in the manufacturing and construction industries has been seriously affected.

Global survey (Fig. 4) depicts a huge cut down in the production order and sales of the industries [12,13]. Fig. 4 reveals that sales and production are continuously declining. Further, the major losses are observed for construction, travel, real state, transportation and manufacturing sectors. Food, healthcare, media and pharma industries are only surviving due to high storage of foods and edible items, increasing use of medicines and medical facilities and large coverage of media showing the nations' scenario. Impact on economy is presented in Fig. 5 from which it can be witnessed that in the absence of the pandemic, economy of all countries was rising [14]. Fig. 5 also shows that even with the normal impact of COVID-19 the economic growth has not been affected so seriously except for some countries like Germany and Italy. However, with the severity of COVID-19, the economic growth has been severely affected. At present, majority of countries suffer severe economic loss with India as the only country which is least affected.

Fig. 6 presents the impact of COVID-19 on global manufacturing industries. It can be observed from it that in 2008–2009,

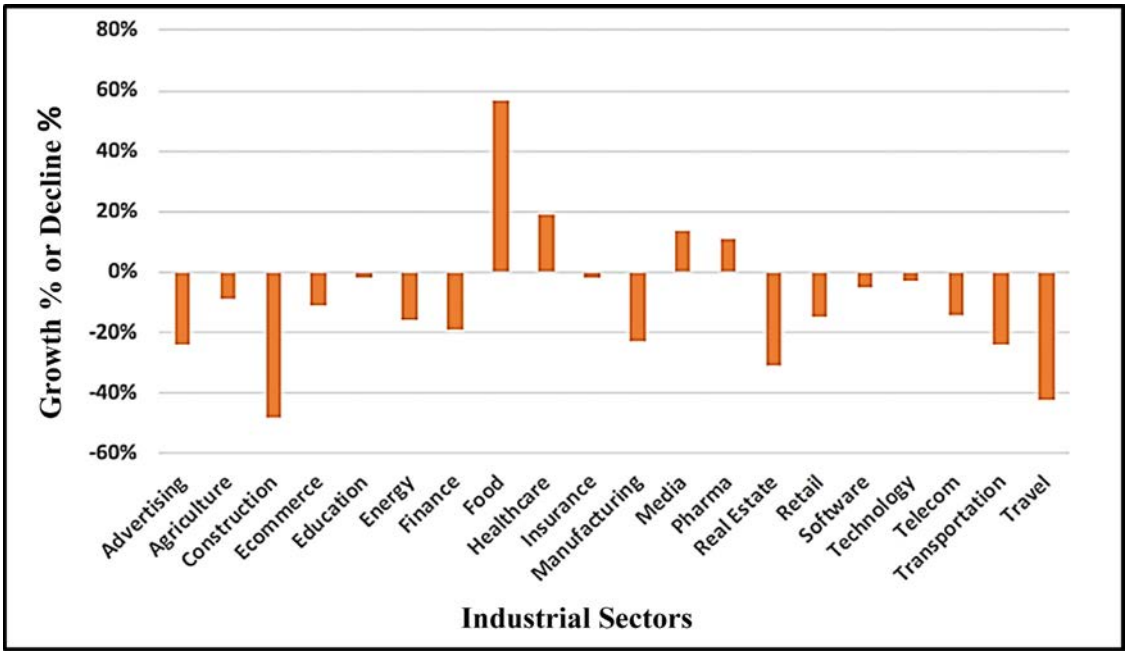

Fig. 4. Conversion growth or decline due to COVID-19 in different industrial sectors [13].

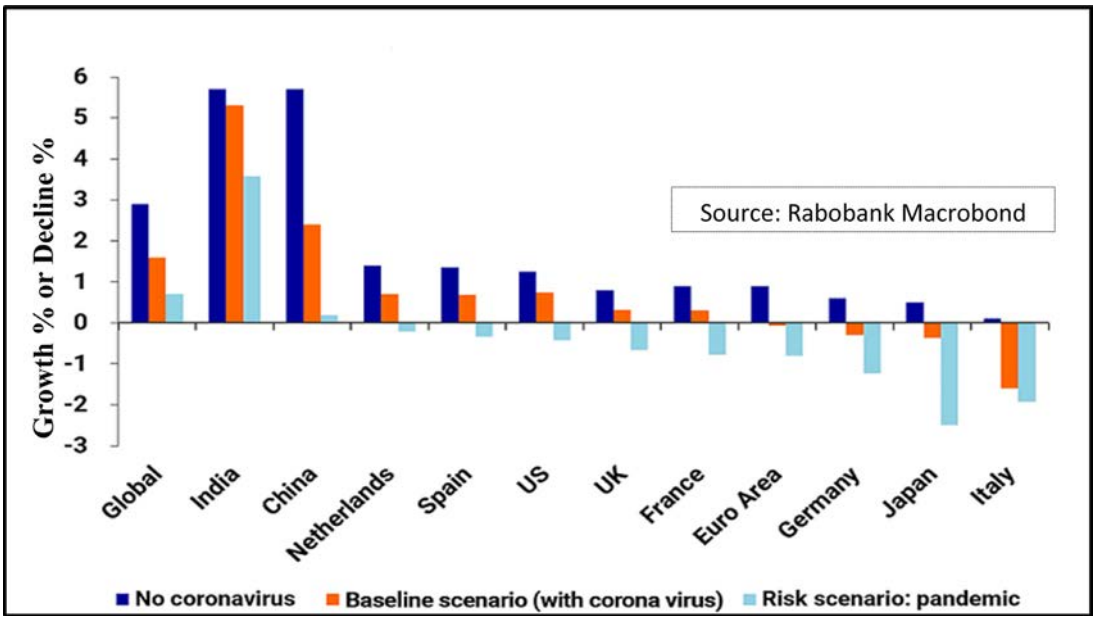

Fig. 5. Economic impact of COVID-19 on different countries [14].

manufacturing-related global production was badly affected due to SARS outbreak. Analyzing the effect of COVID-19 showed that industrial production decreased to −7.5% in 2020 and it will continue to decrease if the effect of the pandemic is not neutralized at the earliest.

Based on the press release, investor relation presentation, annual report, expert interview and market analysis, impact of COVID-19 on smart manufacturing market was presented [16] and graphically it is shown in Fig. 7. It is evident from Fig. 7 that in normal condition the market witnessed steady increase however, due to COVID −19 the market share has been seriously affected and the effect is expected to continue till next 3 to 4 years.

3. Discussions

The accelerated growth rate of COVID 19 resulted in the shortage of medical supplies especially those related to the safety of health care workers, the general public and testing of infected persons. According to one of the reports [17] medical supplies market is expected to increase by $22 billion by 2021 in comparison to 2019. The surge is linked to growing awareness of personal hygiene, expansion of health care locations, increased requirements of personal protective equipment (PPE) kit, particulate-filtering face piece like N95 mask, ventilators and diagnostic supplies. Ability to the rapid fabrication of any complicated geometry of part with short product development time can meet the demand of healthcare delivery systems and medical professionals in the time of pandemic diseases like COVID-19. Considering these requirements, additive manufacturing (AM) technologies emerge as a desirable solution. The role of AM in prevention, diagnosis and monitoring of COVID-19 is presented and importance of AM Global supply chain management is discussed in the following sections.

3.1. Prevention of COVID-19

High demand for personal protective equipment (PPE) has left millions of medical and healthcare professionals unprotected and vulnerable to the virus as the governments were not prepared to deal with COVID-19 pandemic. To stop the rapid spread of infection, healthcare systems require rapid supplies of medical equipment and

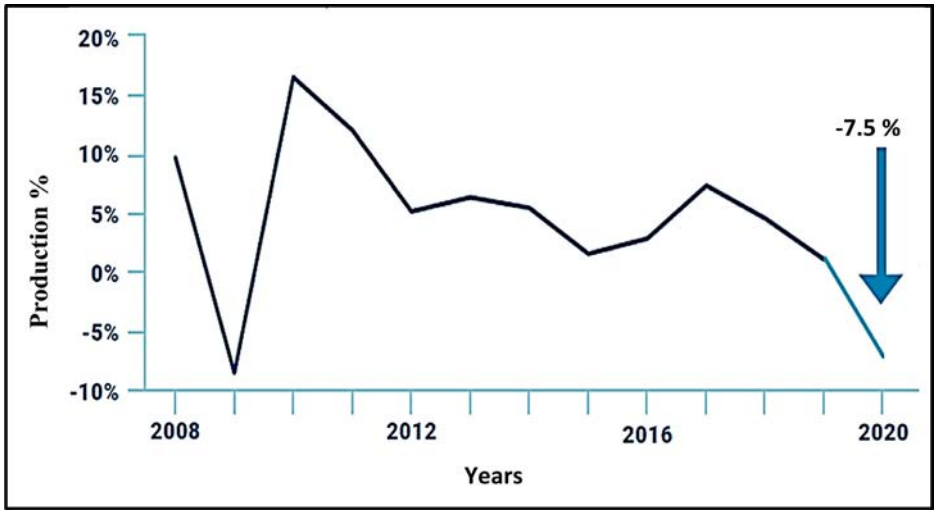

Fig. 6. Impact of COVID-19 on global Manufacturing Industries [16].

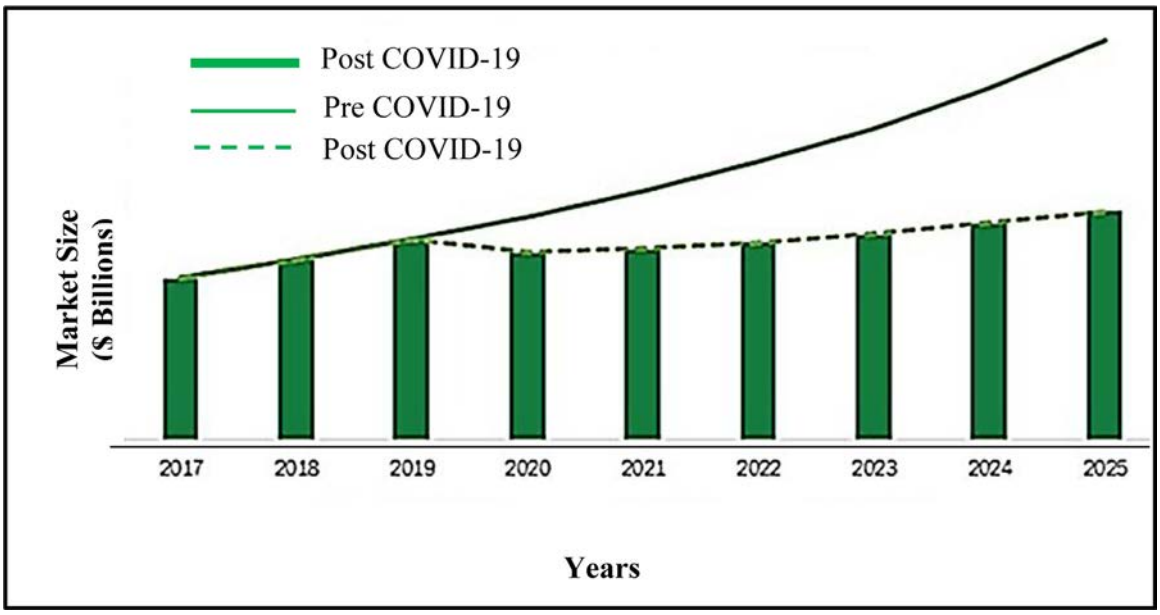

Fig. 7. Impact on smart manufacturing market pre and post COVID-19 [15].

devices in large number. To meet this demand, AM has emerged as a suitable solution. Various PPEs are fabricated with AM technologies to contain the spread of the infection. Fig. 8 shows some of the important PPEs fabricated by AM technologies to prevent COVID-19 spread.

3.1.1. 3D face masks

COVID-19 is an airborne viral infection [18]. Face mask is the basic protective equipment that can be used to prevent the spread of the virus. Considering increase in the infection rate and huge population across the globe, production and supply of the face masks is lacking. To overcome such situation, advantage offered by AM driven technologies is a great relief. AM technologies have already started to counter COVID-19 by offering their pertinent assistances. FDM (fused deposition modeling) is used for fabrication of face masks [18]. An Italian based design maker Roboze's CEO claimed that Agro 500 high-temperature FDM makes moulds from PEEK (Polyether ether ketone) which can be used to produce face mask on mass basis [19]. These moulds are capable of resisting high temperature required to thermoform masks.

As viruses are believed to grow faster in hot weather these masks are more suitable than the conventional ones. A 3D printed respirator masks i.e. RP95 with external filter P3R produced by SIGMA Lutín is one of such kind [19].

3.1.2. Face shield

Face shield is low cost equipment which can be used to prevent infection from viruses to healthcare professionals. It uses a 3D printed frame which is attached to a transparent plastic shield. The fabrication of 3D face shield was first done by Stratasys to reduce the consumption of a large number of face masks in hospitals in pre-COVID-

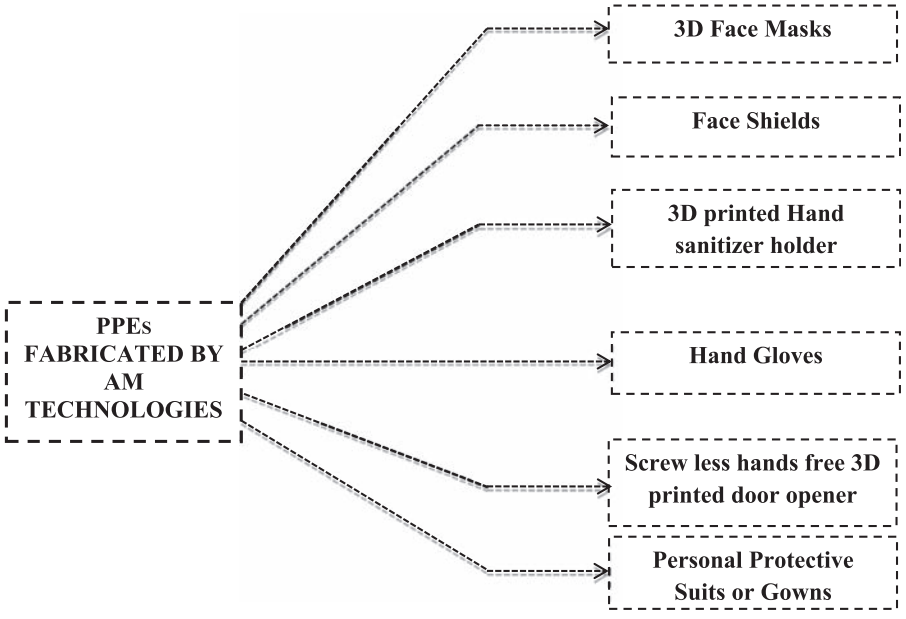

Fig. 8. Additive manufacturing technologies in PPEs fabrications.

19 phase. Stratasys produced 5000 face-shields in a week time by using biocompatible materials and 3D printed parts and even planned to increase the scale at a faster rate [18]. To contribute their role in COVID-19 and to ensure that medical professionals will continue their help to the patients, a large number of other manufacturers and educational institutions with production-grade 3D printers came forward to donate to their capacity. In Spain, BCN3D distributed over more than 400 face shields to the Spanish hospitals.

3.1.3. 3D printed hand sanitizer holder

It is always advisable by medical professionals and healthcare organisations to wash our hands with soaps and sanitizers. Hand sanitizers kill bacterial and other pathogens present in our hands but the reuse and continuous hand contact with the same bottle may cause infection. A wrist clasp which can easily hold a sanitizer bottle for easy access was designed using 3D printing by a Saudi Arabian based engineer specialized in surgical 3D printing. It was a remarkable invention especially for those who suffered from insomniac disorders of washing the sanitizer bottle again and after use. The simple design aids in cleaning hand from time to time without touching the sanitizer's bottle directly and avoiding the infection.

3.1.4. Hand gloves

Hand gloves are used to prevent the contact of our hand with bacteria, viruses and other pathogens. It was observed that during the COVID-19 there was a huge consumption of hand gloves. However, due to shortage, many people used normal and non-disposable plastic as hand gloves which were disposed of after use and remained non-biodegradable. In this situation, the hand shared by AM organizations greatly helped to overcome the shortage. Even, a first 3D printed glove remover was also designed by Rapid Manufacturing AG (Swiss 3D printing service bureau) together with Swiss creative agency Atoll and Zurich-based Pragma Engineering. It greatly helped in dealing with the risk of contamination.

3.1.5. Screw less hands free 3D printed door opener

It was already established in researches that under the ideal conditions coronavirus can remain active in metal material like steel up to 72 h. A recently published study also mentioned that coronavirus infectious properties can range from 4 h to a couple of days on certain materials like steel etc. Every day it is natural for us to take the risk of opening and closing doors of common areas of buildings, hospitals, work centres or shop with the hands which consist of steel parts. CIM UPC designed hands-free 3D printed door handle opener which greatly reduced the risk of directly touching the door handle and getting contaminated by viruses and pathogens.

3.1.6. Personal protective suits (PPS) or gown

To ensure safety of professionals and preventing them from infections, the demand for protective suits shoots up. When it comes to the material selection for protective suits it should be lightweight, free from exposure to contamination, used for multi times and most importantly a disposable one. Besides, other requirements including breathing and splash resistance, particle filtration efficiency and bacteria filtration efficiency are also desired. The preferred raw material is synthetic type, typically polypropylene, polyester, polyethene, or something similar material [18]. There was a high demand for these PPS and in huge numbers. To overcome the shortage, AM technologies are the preferable solution as these materials are common for AM processes and AM allows quick and cost-effective production of these specialized suits to meet the challenge. 3D-printed PPS can be effectively used to provide a physical barrier between medical professionals and infected individual and help in containing the spread of the virus.

3.2. Diagnosis and monitoring of COVID-19

In addition to fabrication of various PPEs as mentioned above, AM driven technologies are also used in the fabrication of different medical devices and facilities for diagnosing and monitoring of the patient during the COVID-19 pandemic. Important applications are listed in Fig. 9 and some of them are discussed in the present section.

3.2.1. 3D swabs

Diagnosis of COVID-19 infection can be done by several testing devices and methods. Some of the common testing methods include blood testing, X-ray examination of the chest, CT scanning of the chest. A testing swab is also a diagnostic medical device which is used for detection of COVID-19 infection. Testing is done by inserting a 6-inch long swab into the nasopharyngeal passage, holding it for 15 s and then rotating it several times. The same procedure is repeated with another side of the nose to ensure the collection of enough material for testing. The swab is then carefully sent to a lab for testing.

Formlabs (Boston-based 3D printing company) is manufacturing 3D printed test swabs to support the COVID-19 diagnostic. The company along with its community of users work to arrange nearly 1000 printers to quickly mass-produce these swabs. 300 3Dtesting swabs can be produced at a time which enables them to produce these swabs on mass basis.

3.2.2. 3D printed manual ventilator

A medical ventilator or a respirator is a machine that helps in the functioning of lungs in case of major injury and respiratory problems. During this pandemic three types of cases are reported: normal common and cold, mild infection and severe pneumonia cases. For the

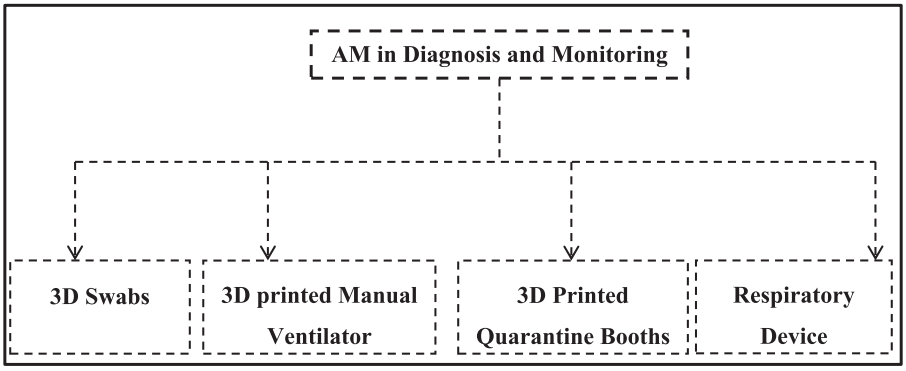

Fig. 9. Additive Manufacturing in diagnosis and monitoring.

first two cases, combination of approved drugs can manage the symptoms. However, if the case is complicated having problems in breathing they are referred to ventilation. Per day cost of ventilation in any good hospital is very high and in countries like India where there are a limited number of ventilators as compared to the population, there is shortage of ventilators during COVID-19. To tackle the high cost and to manage the shortage, AM technologies play an important role. Shortage of ventilator in Italy motivated Dr Lonnie Petersen to produce simple ventilators in a short time to support patients in a crisis [20]. Understanding the serious threat quickly, they were joined by the support and coordination from other faculty and staffs. It was reported that they used 3D printed parts which were attached to a motor and the assembly was used to compress the bag of the manual ventilator. The speed and volume of the compressions were controlled which helped the patient to breathe i.e. it functioned as a medical ventilator. Initially, daily production began with between 50 and 100 units and then production rate was increased according to the requirement.

3.3. Global supply chain management

Supply chain management (SCM) manages the movement of goods and services and it includes processes that are required to convert raw material into the final product. It encompasses the active reorganization of business activities to maximize customers' value and to achieve a viable advantage in the open market. The pandemic created by novel coronavirus has led many organizations to experience some form of disruption in their supply chain which can either be suppliers going offline, a sudden rise in demand, as has been seen with medical personal protective equipment (PPE). During COVID times, AM helps in the development of a variety of components cost-effectively and rapidly [18]. Recently, AM has been used to manufacture a variety of drug delivery systems and medical devices [21]. The advancement in AM combined with the COVID-19 crisis has led to a unique situation and everyone with 3D printing equipment at home could be part of a citizen supply chain. Run by skilled engineers a "maker" community instigated the use of AM for production of PPE and other health care products. Free support and access to their design are provided over the internet. The availability of design and its accessibility helped every individual and firms who have a machine similar to a 3D printer to prepare face masks, shield and other important protective equipment. Even these designs often help in the production of face masks and shield at home. The distribution of these printed items to health care professionals was done in a short time by the community of citizen supply partners in association with industrial and educational institutions. Selective laser sintering (SLS) printer was used by Milan's Issinova technology to design a new valve for an oxygen mask through the scan of the original design was the first example. After the satisfactory performance of the device while testing on patients it was confirmed that the 3D printed valve was excellent and then the company started the production of valves for oxygen masks in several batches [22]. The most popular item that has been shared online and 3D printed by many groups and individuals worldwide was face shields.

4. Post-COVID-19 and additive manufacturing

COVID-19 pandemic has severely affected many industries dependent on international supply chains and affected their home countries. It would take a while for the companies to bring themselves to the original platform but even when the world returns to the normal situation, the industries will not be the alike and only those organizations which will innovate their methodology and processes will survive the new world and grow well in it. Many industries like aviation, textile and automobile have been severely affected from COVID-19 crisis resulting in their complete shutdown. These industries are in danger and their survival is at risk. While they asked for multiple packages from respective governments to save their industry that alone will not save the industry. It is also the responsibility of those within the industry to revisit their approach of doing business and rapidly implement efficient systems. Different sectors of industries like raw material procurements, production and the supply chain should be motivated to save costs and shorten their supply chains and at the same time reduce their dependence on multiple suppliers to run the production process of the companies.

Various industries including automotive and aviation are now devoting and investing in additive manufacturing technologies as they believe that AM technologies can shorten and reduce the time in production and supply chain. In today's time, professional quality additive manufacturing systems are available in all sizes like desktop, benchtop and large formats. These AM systems work efficiently to rapidly fabricate high-performance tooling, replacement, or end-use parts used in the maintenance. AM technologies can be coupled with computer-aided manufacturing to bring flexibility in any type of manufacturing process. They can produce the various products of complex nature from their prototype and use of digital manufacturing [23,24]. Even if the prototype is not available reverse engineering can be used to scan the product and generate the prototype from it. Various companies are even partnering with manufacturers to deploy their 3D systems in operation, maintenance and repair. The best example includes partnering of Etihad airways engineering with BigRep, a large-format 3D printer manufacturer [25]. Even, a lot of organizations have qualified 3D printers, materials, processes and even certain parts that can be 3D printed to be used in a commercial. AM technologies are becoming more essential at a time where the pandemic is becoming a part of our life. AM technologies can truly bring back the industry out of their losses and to bounce back strongly. Companies will have to make necessary changes in business models and manufacturing processes to ensure that the company and the overall industry survives and additive manufacturing can pave the way into the 'Post-COVID-19′ world.

5. Conclusions

COVID-19, a pandemic disease, started in Wuhan and very rapidly it spread to all countries and continents. It has a very high rate of infection and mortality and till date there is no permanent cure. Combination of FDA approved drugs was under trial. The medical and healthcare professionals, researchers and investigators were continually striving to slow down the infection rate and to find the possible cure for the infection. Additive manufacturing (AM) technologies have emerged as a potential solution for application in COVID-19 crisis. The rapid supply of PPEs and other medical facilities can be met using AM or 3D printing technologies. AM technologies having not only the capability of rapid fabrication of medical devices and facilities but they are also used in the diagnosis and monitoring of the pandemic. AM technologies are very helpful in managing the global supply chain and the community of citizen supply chain in collaboration with industrial and educational institutions. They organized and led the foundation of the enormous network in a short time to distribute 3D-printed items to health care professionals. It is proved that AM technologies have helped to overcome the COVID-19 crisis. Even though there is a huge potential of AM in a pandemic scenario but they do have some limitations.

These limitations are:

1. According to FDA (Food and Drug Administration), face masks and respirators printed by 3D-printing serve the purpose they are designed for but they cannot provide the same fluid barrier and air filtration protection as masks and N95 respirators.
2. The thorough guidelines on the role of 3D-printed PPE for protection of virus transmission are not given.

3. The designing and application of 3D printed PPEs following FDA guideline is still challenging for AM or 3D Community and can be considered as a future assignment.

Declaration of Competing Interest

The authors daclare that they have no competing interests.

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