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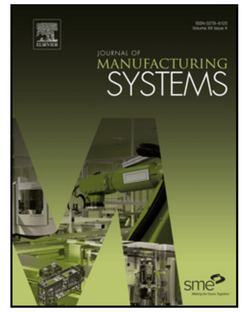

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Aamer Nazir, Aashir Azhar, Usman Nazir, Yun-Feng Liu, Waqar. S. Qureshi, Jia-En Chen, Eisa Alanazi

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The rise of 3D Printing entangled with smart computer aided design during COVID-19 era

Aamer Nazir[1,2,*], Aashir Azhar[3], Usman Nazir[4], Yun-Feng Liu[5], Waqar. S. Qureshi[3,7] , Jia-En Chen[6], Eisa Alanazi[7]

[1]High Speed 3D Printing Research Center, National Taiwan University of Science and Technology, No. 43, Section 4, Keelung Road, Taipei 106, Taiwan, R.O.C

[2]Department of Mechanical Engineering, National Taiwan University of Science and Technology, No. 43, Section 4, Keelung Road, Taipei, 106, Taiwan, R.O.C

[3]Robot Design and Development Lab, NCRA, NUST C of E & ME, Rawalpindi, Pakistan

[4]Department of Civil Engineering, University of Sargodha, Pakistan

[5]Department of Mechanical Engineering, Zhejiang University of Technology, China

[6]Medical 3D Printing Center, Department of Biomedical Engineering, National Defense Medical Center ,Taipei, Taiwan

[7]Department of Computer Science, Umm Al-Qura University, Makkah, Saudi Arabia

[*]Email of the corresponding author: aamernazir.an@mail.ntust.edu.tw

Highlights:

- In this article, we present an extensive review on the utilization of 3D printing technology in the days of pandamic. We observe that 3D printing together with smart CAD design show promise to overcome the disruption caused by the lockdown of classical manufacturing units specially for medical and testing equipment, and protective gears. We observe that there are several short communications, commentaries, correspondences, editorials and mini reviews compiled and published; however, a systematic state-of-the-art review is required to identify the significance of 3D printing, design for additive manufacturing (AM), and digital supply chain for handling emergency situations and in the post-COVID era. We present a review of various benefits of 3DP particularly in emergency situations such as a pandemic. Furthermore, some relevant iterative design and 3DP case studies are discussed systematically. Finally, this article highlights the areas that can help to control the emergency situation such as a pandemic, and critically discusses the research gaps that need further research in order to exploit the full potential of 3DP in pandemic and post-pandemic future era.

Abstract

During the current Pandemic, seven and a half million flights worldwide were canceled which disrupted the supply chain of all types of goods such as, personal protective gears, medical health devices, raw materials, food, and other essential equipments. The demand for health and medical related goods increased during this period globally, while the production using classical manufacturing techniques were effected because of the lockdowns and disruption in the transporation system. This created the need of geo scattered, small, and rapid manufacturing units along with a smart computer aided design (CAD) facility. The availability of 3D printing technologies and open source CAD design made it possible to overcome this need. In this article, we present an extensive review on the utilization of 3D printing technology in the days of pandamic. We observe that 3D printing together with smart CAD design show promise to overcome the disruption caused by the lockdown of classical manufacturing units specially for medical and testing equipment, and protective gears. We observe that there are several short communications, commentaries, correspondences, editorials and mini reviews compiled and published; however, a systematic state-of-the-art review is required to identify the significance of 3D printing, design for additive manufacturing (AM), and digital supply chain for handling emergency situations and in the post-COVID era. We present a review of various benefits of 3DP particularly in emergency situations such as a pandemic. Furthermore, some relevant iterative design and 3DP case studies are discussed systematically. Finally, this article highlights the areas that can help to control the emergency situation such as a pandemic, and critically discusses the research gaps that need further research in order to exploit the full potential of 3DP in pandemic and post-pandemic future era.

Keywords: Additive Manufacturing; 3D Printing; Design for AM; COVID-19; Supply Chain

1. Introduction

The recent pandemic known as novel coronavirus [1] (COVID-19), is an unprecedented situation in modern globalized world that has created an extraordinary emergency. It has been affecting all sectors of life, in particular, the medical, aviation and supply chain [2]. The cost of the pandemic for the civil aviation industry is about 50% decline in revenue, due to cancellations of 7.5 million flights worldwide, and country-specific restrictions [3]. In some cases, the cargo flights that deliver much-needed medical equipment and medicines have also been canceled to curb the spread of COVID-19. The health sector has been facing several issues especially the occupational safety and shortage of personal protective equipment (PPE) which is crucial for the front line medical workers to protect both themselves and their patients [4]. The supply chain of all types of goods in particular the protective and medical health devices, medicines have been affected severely; therefore, created the need for advanced technologies and solutions to step in and tackle the shortage of PPE, medicine and medical devices, and traditional supply chain limitations [4,5].

3D Printing (3DP), also known as additive manufacturing or rapid prototyping is an emerging technology [6] for the layer-by-layer fabrication of personalized and customized parts of any complexity, directly from the computer aided design (CAD) file as input [7]. Different companies have been providing 3D printable models on online clouds that can be downloaded by any user worldwide; thus realized cloud manufacturing [8]. Due to digital design and manufacturing, this technology is capable of quick design and development of parts that can be revised quickly in lesser cost and time; thus, fulfill the shortage of parts and supply chain limitations [9]. There are several examples of successful application of 3D Printing in particular during the emergency situation of the pandemic. Erickson et al. [10] used design for additive manufacturing (DfAM) techniques for retrofitting of arthroplasty helmets to be used as PPE. They have explained the steps from design to safety check testing, which can be adopted for any other equipment retrofitting or reverse engineering. Amin et al. [11] presented the workflow of 3D Printing of face shields to protect oral and maxillofacial surgeons. They divided the whole process into four phases including design, digital file preparation for manufacture, 3D Printing, and finally assembly.

3D Printing experienced huge popularity during the last two decades due to democratization. In addition to that, recent COVID-19 pandemic situation realizes the need of 3D Printing to an unprecedented level. Due to direct digital manufacturing [12] characteristics of 3DP, the 3D models of any complexity [13,14], designed in any part of the world, can be downloaded in any country worldwide, even in remote areas, and can be 3D Printed (according to demand) [15] in any locality of any country using the readily available or recycled materials [16–18]. Figure 1 shows the availability of 3D Printers worldwide which implies that the strategically deployed 3D Printers worldwide [19] have the capacity of additive manufacturing of a diverse range of products (locally near the point of use) their digital models are already shared and available on internet clouds [8,20].

Figure 1 3D Printing map of the world by 3D Hubs [21]. These strategically deployed 3D Printers worldwide have the capacity of additive manufacturing of a diverse range of products while their digital models are already shared and available on internet clouds

When compared with traditional design and manufacturing methods, the lead time is significantly higher with complex distribution networks which is based on product delivery physically rather than digital distribution of CAD models. In addition, it is not feasible and economically justifiable to manufacture the product everywhere in the world near the point of use. Using 3DP, reconfigurable manufacturing can be realized without making considerable changes in the production process [22]. For example, many big firms in United states and Europe such as Nisan, Volkswagen, Ferrari, BMW, and Airbus used their 3DP facilities (selective laser sintering, FDM, and SLA) for the fabrication of medical devices and PPE to support the shortage of these devices [5]. Furthermore, it is very difficult and hazardous to fabricate an accurate part using traditional manufacturing methods without proper training and certification. On the other hand, 3DP is user friendly and much easier to use, even for the higher school students. A large number of makers and students under the leadership of a skilled engineer can design and 3D print emergency needed products by using the printers available at home, industrial and academic research institutes, maker's hub or an academic university.

The literature review has revealed that there are a handful of short communications, commentaries, correspondences, editorials and mini reviews have been compiled and published yet; however, a systematic state-of-the-art review is required to identify the significance of

3DP, design for AM, and digital supply chain for handling emergency situations and even the post-COVID era. In this article, the authors aim to present a review of various benefits of 3DP particularly in emergency situations such as a pandemic. Furthermore, some relevant iterative design and 3DP case studies are discussed systematically. Finally, this article highlights the areas that can help to control the emergency situation such as a pandemic, and critically discusses the research gaps that need further research in order to exploit the full potential of 3DP in pandemic and post-pandemic future era. We observe that 3D printing together with smart CAD design show promise to overcome the disruption caused by the lockdown of classical manufacturing units specially for medical and testing equipment, and protective gears

2. Methodology

Several procedures were taken to ensure a high quality review of the literature. First, reports and papers were searched independently on Google and databases: Google Scholar, Scholars Portal Journals and Research Gate on the broad range of key terms including COVID-19, C-oronavirus, SARS-COV-2, 3D printed ventilator parts, PPE, Pandemic, Impact of 3D Printing, 3D printed face shields distributed manufacturing and critical supply shortage. Secondly, a comprehensive study of blogs, articles, and news published on 3D printing in the COVID-19 pandemic was conducted. The data is gathered from a wide range of popular 3D printing blog websites including 3D printing industry, 3Dprinting.com, 3ders.org, 3D print.com, All3DP and Shapeways Magazine etc. Thirdly, from this data, the different cases were deeply studied and solid sources like the researcher interviews, Universities portal, and Company websites were found for references and to extract the research article linked. The reference section for each article found was search in order to find additional articles.

3. Importance and Benefits of 3D Printing

The unique characteristics of 3DP enables it to be exploited for DDM of personalized products with complex shapes; therefore, AM technologies are being used in all major industries mentioned in [23]. Due to the wide scope of applications, 3DP has been used in a diverse and broad array of industries; however, all of them are exploiting more or less similar type of capabilities of 3DP summarized by Lipson and Kurman in [24]. Based on the scope of the present study, only those benefits of 3DP will be discussed which can be useful (based on authors, knowledge) to control the emergency situation such as a pandemic.

3.1 Direct Digital Manufacturing of Customized Parts

Direct digital manufacturing (DDM) refers to the creation of end use parts and components through the use of additive manufacturing. It is also sometimes referred to as rapid prototyping (RP), however, the parts produced through DDM do not have the same usage as the parts produced through RP. The parts produced through RP are used for a quick analysis and communication for design intent whereas the parts produced through DDM are for use by the customer. Before delving into the DDM and its advantages, it is necessary to take a look into the history of manufacturing, the traditional manufacturing processes and the reason the manufacturing industry is poised to transform itself into a DDM phase [25].

In the 1950s the military industrial complex adopted wide usage of numerically controlled (NC) machines (the precursors of computerized numerical control machines) due to its need for mass producing parts with limited tolerances. This adoption of NC's was the first step in transforming the landscape of machine workshops. After the adoption of digital NC's, followed by CNC's, the landscape has once again transformed from blue collar jobs in the workshop floor, to the white collar jobs of Computer Aided Design (CAD). CAD and Finite Element Analysis (FEA) are some of the most important catalysts which have transformed the manufacturing industry from thousands of people working on lathe and milling machines, to a few hundred people designing the parts using CAD, analyzing them through FEA, and finally producing them through CNC machines. This is true for every industry open to pervasive automation. While in the 1980s most of the jobs in the manufacturing industry were actually directly involved in using the machines to manufacture equipment, in the current age, most of the jobs involve supervision and upkeep of machines. This has resulted in some cases in as much as a 90% decrease in the jobs required to manufacture at the same volume because the slack has been picked up by robots [26]. The Tesla plant in California uses 160 fully automated robots to manufacture 400 cars per week.

The traditional manufacturing refers to the processes which create the final part by taking in a block of material, and cutting away the material to create the end product, in a similar manner to how a sculptor starts from a block of rock, and ends at the statue. These processes are severely limited due to the very nature of their manufacturing techniques. In general, the greater the complexity of the part, the higher will be the cost. This implies that these processes lend themselves easily to mass manufacturing where the final part is broken down into simple components which are then assembled. However, with DDM, complex parts can be printed in one go instead of being broken down into components. One of the famous examples is the use of additive manufacturing by GE [27]. In 2018, GE created a civilian turboprop engine using AM of advanced alloys. This allowed GE to create an engine from just 12 parts as compared to the 855 separate components, resulted in a weight reduction of more than hundred pounds, improve the fuel utilization by 20% thereby increasing its power and simplifying maintenance. This great leap in manufacturing was possible through the use of DDM.

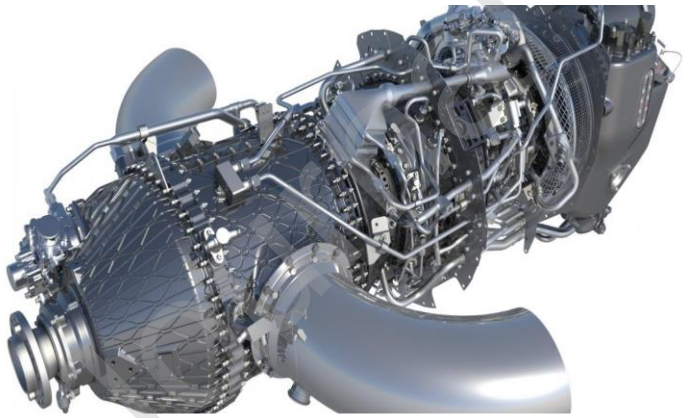

Figure 2 Advanced Turboprop engine build using additive manufacturing by GE [27]. Design for AM was exploited to design this engine from just 12 parts as compared to 855 components when designed for traditional manufacturing methods

For NASA, DDM allows for creating parts in space by just sending the raw material and the printer along. This was demonstrated when a wrench was designed on earth and sent to ISS where it was manufactured using 3d printing and used [28]. If it had been a critical component, the astronauts would have had to wait until the next supply mission to get the equipment, however, with the help of DDM, the astronauts can now manufacture what they need on the ISS. This allows for a greater versatility in equipment needed, and is also a critical step for the mission to Mars.

Figure 3 Wrench printed in space on the International Space Station [28]

3.2 Complexity Does not Increase the Cost and Time

The biggest advantage of DDM is that it lends itself to a change in manufacturing very easily. For traditional manufacturing parts, the turnaround time is very high. After the creation of design and its approval, to manufacture the part would require the design of its toolings and fixtures which would take more time. This would be followed by more testing and analysis before the final part can be created. All of these steps require a lot of time, expertise, and material to create the final part. In an emergency situation such as a global health pandemic, the manufacturing industries take a big hit due to the disruption in supply chains. Since most of the manufacturing industries use Just In Time supply chain, and disruption can lead to a long waiting time. Furthermore, in a disruption in the supply chain, it is imperative to conserve and recycle the material, which is difficult for traditional manufacturing. For example, in the aviation industry, the buy-to-fly ratio is 33 which implies that every 1kg of material used in an airplane, 33kg of the raw material needs to be bought, most of which will be wasted during the subtractive manufacturing.

DDM allows us to bypass all these issues, and create the final component in days compared to the weeks it would take to ramp up production through traditional manufacturing to meet the demand. By using the virtual environment of design and analysis, the production of the part can be optimized without actually creating and testing the part. This step is very difficult for traditional manufacturing processes, where complexity can lead to a disproportionate increase in cost. In contrast, DDM features complexity-for-free. This means that the complexity of the part manufactured using DDM has a very limited (and in some cases zero) impact on the final cost of the part.

In the recent Covid-19 pandemic, the traditional manufacturing industries almost shut down due to lockdown measures put in place to limit contact of humans, and due to the disruption in the supply chain. To counter this, DDM using 3D Printing stepped in to pick up the slack in manufacturing. Some of the most famous examples are the printing of life saving components of ventilators, entire ventilators themselves, face shields, and personal protective equipment.

A team of Italian volunteers made and supplied 3D-printed versions of a vital medical device, respirator valves, which saved the lives of many COVID-19 victims. They were able to design, refine and print hundred life saving respirator valves in just 24 hours for a hospital that had run out of them [29]. The valve connects breathing patients in intensive care to machines. The 3D printed version costs less than a pound each to manufacture and the prototype took only 3 hours to design.

Figure 4 Respiratory valves designed and printed in just 24-hours [29]

The role of DDM in shaping the landscape of manufacturing industries cannot be denied. As time goes on, DDM will continue to have an increasingly greater impact on manufacturing. Adoption of DDM will lead to a change in the supply chains and specialized economies, and will allow for local manufacturing of parts in case of emergencies.

3.3 Rapid Iterative Design for AM Procedure

The iterative design process is a methodology based on a cyclic process of prototyping, testing, analyzing, and refining a product or a process. Based on the results, the most recent iteration of a design, changes and refinements are made. This process is opted to improve the functionality and quality of a design. In traditional manufacturing, iterating a product or a system is a very time consuming and costly process since a change in design usually means change in the whole manufacturing process including tools and fixtures. This will cause a delay in meeting consumer demand especially during the current world pandemic where there is a significantly large demand in different products like face shield holders and medical ventilators which are very essential in the fight against COVID-19. Due to the pandemic supply for these critical medical devices has fallen significantly to the extent in which it is impossible to meet hospital demands with the traditional way of supplying these devices. AM makes it simple and possible when it comes to iterating prototypes and delivering products in a very short amount of time. It allows designers and manufacturers to ideate and iterates fast. The faster the iteration process can be, the more successful products will be delivered to those in need. AM brings not only speed but the freedom to design products which aim in serving the intended function regardless of the complexity of the product.

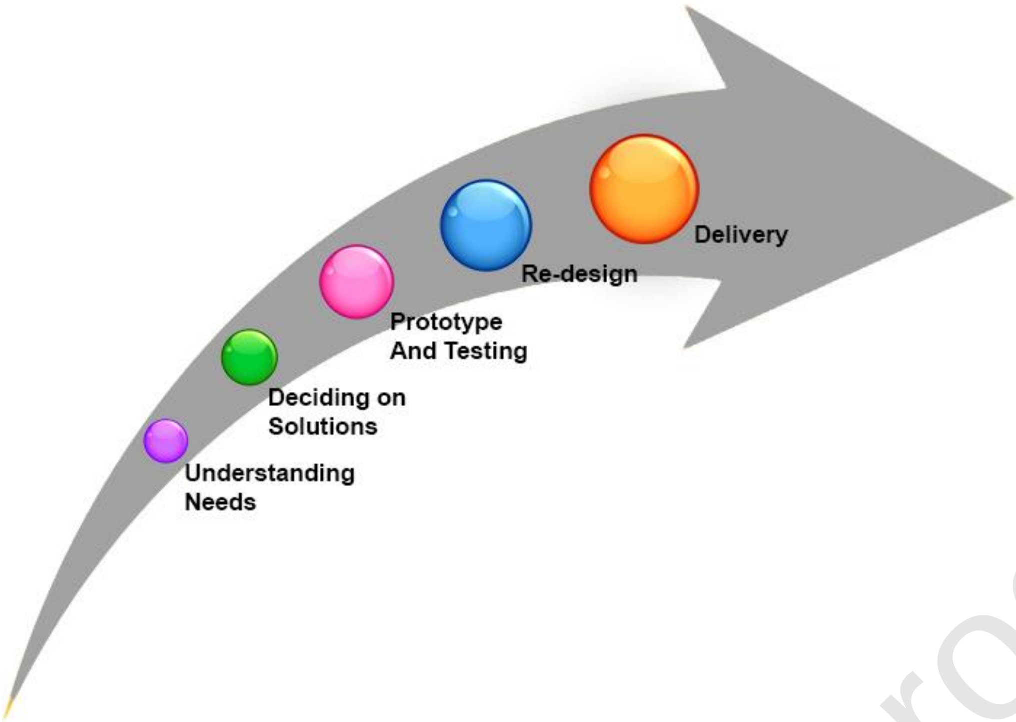

Figure 5 Quick iterative design steps in AM. This design strategy was employed for the creation and realization of medical and life saving devices during COVID-19 pandemic

To illustrate the rapid iteration design capabilities of AM, real-life case studies are discussed as examples as follows.

The first example is from the USA where a group of makers in Charlotte got together with students and teachers at Charlotte Latin School and UNCC to for Charlotte MEDI (Medical Emergency Device Innovation) with the hope of producing face protection shields for health care workers in the Charlotte community [30]. They started with an open-source face shield design made by Prusa, and after just a few days of minor modifications they were able to prototype the first few dozens and get them in the hands of nurses and doctors at local hospitals for testing. After the initial prototypes have been tested by medical professionals, they took feedback from those health care professionals and modified the designs according to the need within a matter of just 4-5 days. After just 10 days of forming, their goal was to deliver 15,000 shields per week using the local community network of 3D printers and local manufacturing companies. But with their effort and the capability of 3DP, they have reset their goal to deliver 100,000 shields. From the time they made their first prototypes (March 20, 2020) they were able to print 5000 face shields per day by March 29, 2020 withing just 9 days. In these 9 days, they were able to modify and iterate their designs according to the feedback given by the health care professionals.

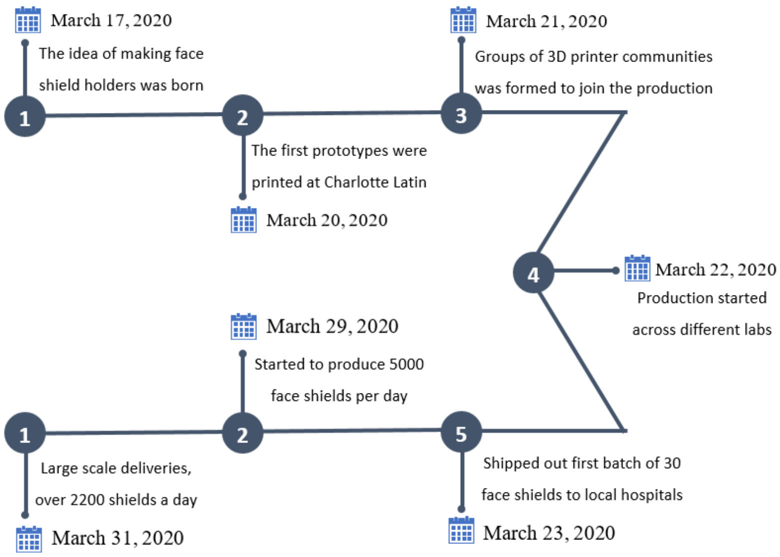

Figure 6 Timeline showing the process of making face shields from idea generation to final delivery

Charlotte MEDI was able to iterate different designs and deliver face shields less than one month's time due to the rapid nature of 3D printing. They have delivered 106,299 shields to different hospitals.

Figure 7 Face shield made by Charlotte MEDI [30]

Also, a FabLab located in Taiwan managed to 3D print face shield holders for hospitals using 3D printers. They were able to print not only more than 700 face shield holders in just 15 days, but also significantly decrease the size of face shield holders which will make it more comfortable to use and cost effective. They were able to design and iterate different versions of face shield holders, glass and forehead version, in a few days.

Figure 8 Comparison of size between the traditional(left) and 3D printed face shield holder

From the above case studies, we can see that the rapid nature of AM and design for AM makes it possible to design, iterate, produce and deliver products much faster and in quick response time than traditional manufacturing. These advantages are especially being exploited by the AM industries to supply medical care devices and PPEs to help fight against the current global pandemic.

3.4 Digital Supply Chain

In accordance with academic studies [31,32], AM has potential to have remarkable impact on the production and distribution of products which reduces the complexity of the supply chain. The major advanatage of AM lies in the consolidation of the components into a single product consequenlty decrases the number of assembly and pre-assembly steps in the manufacturing. AM also decreseas the inventory complexity for the operation manager. The major implication of AM is customized product in accordance with the prefernece s of the customer which reduce cost and increase profit. Hence, supply chain can evolve with changes in the marketplace.

The major affect of AM on the traditional supply chain can be clearly illustrated through four key factors which include cost savings, speed responsiveness, quality imporvement, and postive enviromental impact.

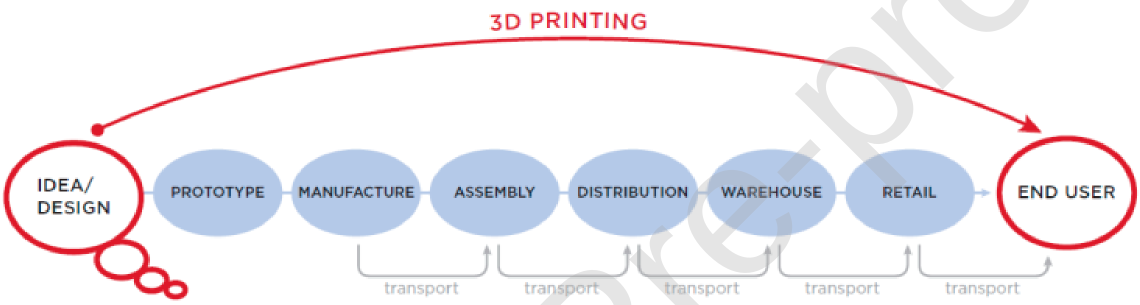

Figure 9 How AM shortens the supply chain involved between design to final product to end user [32]

Some of the main differences between the traditional supply chain and additive supply chain can be discussed in the table.

Table 1 Traditional supply chain versus AM alternative

Traditional Supply Chain	**AM Impacted Supply Chain**
Push supply chain	Pull supply chain
Long lead times	Shorter manufacturing lead time
High transport costs	Reduced transportation cost
Complex distribution networks	Reduced inventory
Dependency on economies of scale	Dependency on economies of scope
Lengthy response to customer demand	Quick response to customer demand
Challenging management of demand uncertainty	Easier management of demand uncertainty
High level of required inventory	Reduction in required inventory
Manufacturig far away from point of use	Manufacturing closer to point of use
Using intermediaries in the global supply chains	Supply chain disintermediation
Supply chain disruptions-broken machines, regional turmoil, or shipping delays	Hedge against disruptions

The AM can benefit supply chain through reduced material waste compared to traditional manufacturing, enhance the flexibility , decrease production cost, customized products for customer demands, and perform decentralise production. The manufacturer would need new innovative methods for product distribution, product delivery to end users and new sources of materials. Additive manufacturing ecosystem are capable to disrupt the supply chain mechanism in which the product is manufactured by the retailor which is synchronized with the demands of the end user [33]. The additive manufacturing would overtake the traditional manufacturing and supply chain. The mass customisation of products will become less expensive. Means that , the consumer would also played a part in production manufacturing. The supply chain become more effiencent and localized.

4. Case Studies

In a recent official statement, the Food and Drug Administration (FDA) has been disclosed the emergency use authorization guidelines for the possible use of 3D printed PPE, respirator prototypes, 3D printed connectors and other parts of ventilators; however, they have mentioned that 3D printed respirator are not as efficient as FDA-approved N95 respirators [34]. Therefore, many researchers and research institutions have been working on the design and 3D printing of several life saving equipment in the context of the COVID-19 pandemic. Some of the most important case studies are included in this review article.

4.1 Air-Purified Respiratory Hood

In COVID-19 pandemic situation, medical staff wear only N95 mask and a face shield while performing an aerosol-generating procedure. There were shortages of personal protective equipment (PPE), and surgeons who used headlights and loupes facing difficultly while using these in conjunction with face shields [4]. In such a situation, , Melissa M. Erickson initiated the utilization of unused arthroplasty helmets will represents a probable solution to PPE shortage. The modification ,quality testing and retrofitting of arthroplasty helmet is performed with the collaboration of Duke university of Pratt School of Engineering. [35–37]. This retrofitting arthroplasty helmet leads to power air-purifying respirator (PAPRs) that pull air through a HEPA filter into the hood to create positive pressure with air moving out. The person wearing that respiratory hood only receives filtered air means the minimum risk of being infected.

The concept developed was to use the 3D printing approach for creation of an adaptor for the Flyte helmet by using Formlabs printers with durable material. The adaptor is a single component called the manifold. The engineering team design and created the final adapter just in 12 days, they come up with different alterations in design while testing to make the final manifold, which is only possible because of 3D printing [10].

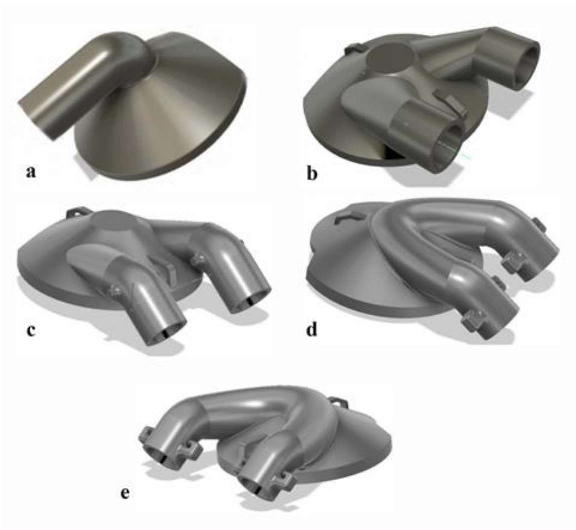

Figure 10 Respiratory hood design iterations by employing design for AM methods (a) 2nd day design, (b) 4rth day design, (c) 6th day design, (d) 8th-day design (e) 12th-day final design [10]

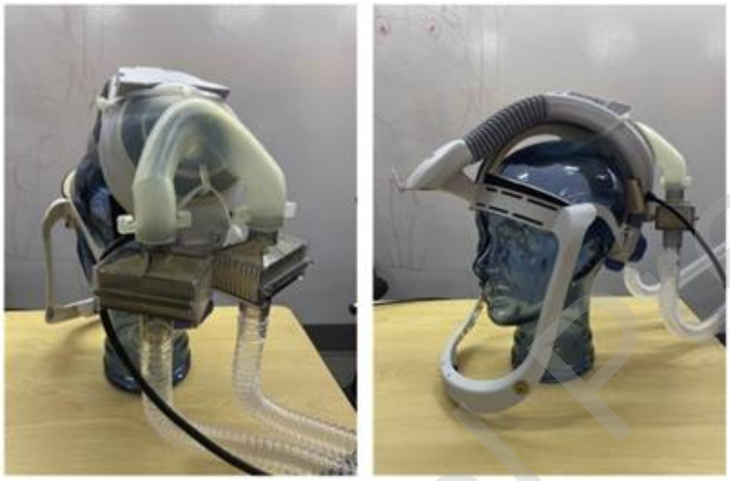

Figure 11 The specialized breathing circuit filters are binded to the manifold, secured, anesthesia tubing is attached [10]

On the other hand, people from different regions of the world start working on these respiratory hood. The researchers from the University of Southampton in the UK made their prototype just in one week [38,39]. With their open-source CAD models and research data, developing countries also easily made these respiratory hoods. For Example, The National Centre of Robotics and Automation (NCRA) in Pakistan fabricated their prototype easily in 4 to 5 days.

4.2 COVID-19 Specimen Collection Kits

The Nevada State Public Health Laboratory (NSPHL) was the first public health lab to manufacture specimen collection kits while using 3D printing at the start of the march 2020. At that time, the pandemic was on the peak and there was a huge short supply of COVID-19 collection (testing) kits. It was the combined contribution of scientists from the Department of Microbiology and Immunology at the University of Nevada, Reno School of Medicine (UNR Med) with NSPHL and their aim to create and manufacture their own supply [40]. The Kit is used to collect a specimen through nasal swabbing of patients. The complete testing kits manufacturing process involves two parts, one is creating 3D printed testing swabs and the other is production viral transport media (VTM) [41–43]. The Lab has the ability on most days to manufacture an average of 1000 specimen collection kits which is only possible as UNR Med is partnering with Makerspace at the University of Nevada, Reno Innevation Center, by utilizing Formlabs printer to print 1000 swabs. One printer prints on an average of 260 swabs in 24 hours. They had purchased one printer and other three was used through a partnership with Reno Innevation center [40].

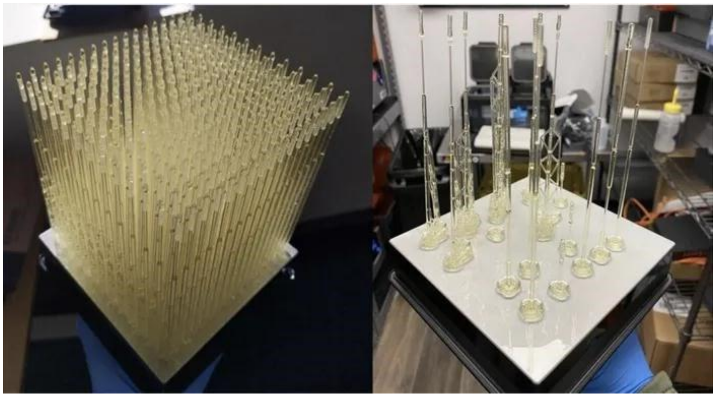

Figure 12 3D printed nasal swabs [41]

Other companies all other the world also start designing and printing these swabs like University of South Florida Health in UK joins with Formlabs to print 5000 swabs per day for their hospitals with 3D printers and the team at University of California San Diego with the help Markforged Company design and print 10,000 swabs per day [44]. The different developers committed to the Open COVID Pledge posted their designs on different platforms like Websites and Github etc [45]. The 3D printed Swabs empower the hospitals by giving them another option to make swabs on-site So, they have not to worry about the next shipment arrives in the critical supply chain fails [42]. In another case study, 3D Printing Tech is using the MfgPro230 xS, SLS printer of XYZprinting for mass production of the nasal swabs during the pandemic. Not a single failure of production print thousands of swabs at a time to combat the COVID- 19 [46].

4.3 3D Printed Ventilator Circuit Splitter

The current crisis of COVID-19 had a great adverse impact on every segment of the world especially on the health sector. The uprising of virus resulted in a widespread ventilator shortage throughout the world. Furthermore, the disruption of the global supply chain prevents the movement and production of medical devices. The idea of using a single ventilator for multiple patients was introduced using six Briggs T-tubes and a Puritan-Bennett 840 Series ventilator which was tested in four sheep which contemplates human size [47,48]. The Briggs T-tube is a complex instrument not easily available in the past. Now, the digital design easily available via internet through the help of 3D printing techniques. The 3D printing allowed mass production of Briggs T-tube at the place of need. The Royal Women's hospital in Australia has produced a flow restrictor apparatus and splitter apparatus. San Rafael, CA, USA had used Fusion 360 for computer-aided concepts and design [49].

Figure 13 Flow splitters and a single flow restrictor [49]

The ventilator splitter is printed using several inexpensive FDM 3D printers. The time for production was set 6 hours of desktop 3D printer (Original Prusa i3 MK3S, Prusa Research, Prague, Czech Republic) that incorporate one complete set of two splitters including inspiratory and expiratory limbs and one inspiratory flow restrictor. The raw material cost was Australian USD 1.00 [49].

4.4 Ventilator Venturi Valve

During the uprising of coronavirus in Italy towards the late march, a hospital of the town Chiari lacked a basic component of a ventilator known as "Venturi valve" [50]. The component is required to connect to the face mask of the patient to deliver oxygen at a variable concentration. The major issue regarding the valve is that it can only be utilized for 8 hours and cannot be reused. The problem was taken care of by Cristian Fracassi, CEO of the 3D-printing startup Issinova, who through the process of reverse engineering developed hundred life-saving respirator valves in a 24 hours for the hospital [51]. The 3D-printed version cost almost one euro to manufacture and the prototype took 3 hours to design. The STL file is not been shared due to copyright issues. The medical and copyright issues should be considered during the manufacturing process of Venturi Valve. Such an effective tool could be the difference between life and death. A GrabCAD user named Filip Kober has created a Venturi Valve model and made its availability free as open source design on internet [52]. With a combined effort with their partners at Shapemode, the stereolithography technology is used in 3D printing of the device and it has proper dimensions.

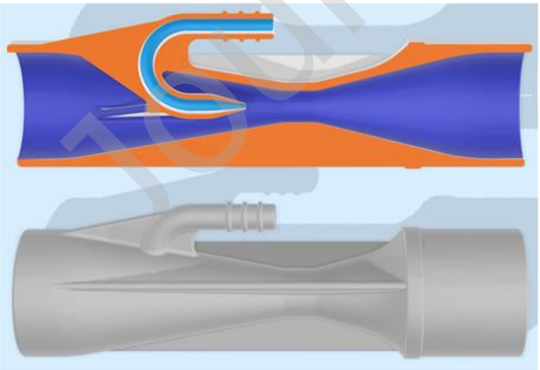

Figure 14 Open source Venturi valve [51]

4.5 Facemasks

NanoHack 3D printed mask (recyclable and can be reused)

In the amid of this pandemic, the whole world is going through the least of the PPE especially the lack of professional FFP2/3 face marks for doctor's nurses and patients. The whole world is looking for an alternative solution which is available in the form of 3D printing that is easily accessible with least cost and availability around the globe. The introduction of the smartphone with a camera is readily available for all people who could perform 3D individualized scanning of face and send the OBJ format data file to designated location through email in less than 2 minutes 30 seconds [53]. The 3D Infinity has started this initiative by making STL file of the reusable component of custom face mask as open source design for others to follow. A 3D printer had a capacity to print 60 individual face masks within 24 hours. The post processing includes standard sterilization for 15 minutes at 135 Celsius temperatures [54].

Figure 15 (a) Custom-made individualized 3D printed protective face mask, (b) filter membrane for support, (c) polypropylene (PP) non-woven melt-blown particle filter, (d) Three-Dimensional image of the prototype [54]

3D printed customized face seal N95 template

The customized N95 FFR face seal marks are developed which are experimentally validated by using a sensor system. The laser scanning of the headforms is done to design the geometric model of face seal and later fabrication is done using FDM technique of 3D printing. The designed FFR face seal must provide comfort in breathing to wearers and must be fit on the face of the wearer. The Allcct Technology, Wuhan, China has used FDM machine to manufacture FFR face seal marks to optimize the protective performance of it [55].

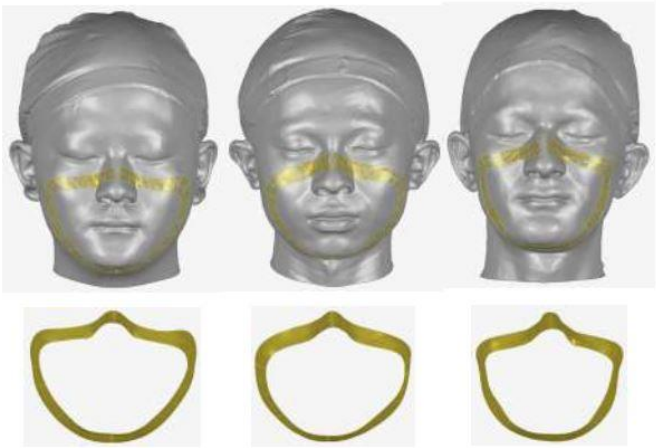

Figure 16 3D CAD models of FFR face seals for three subjects [55]

4.6 3D Printed Pills

As for now, there are no specific antiviral or vaccines for the treatments of the patients. The 3D printing technologies including inkjet, powder extrusion and fused filament allow us to make 3D printed pills [56]. A special kind of coaxial needle extrusion 3D technology is used to print 3D printed pill and create a combination with variance concentration of drugs. Mainly, it uses a small nozzle to place thin disc-shaped layers of powders and utilize microscopic droplets of liquid to bind the materials. From the research and development, it is concluded that 3D medication printing allows us to rapidly print the lopinavir/ritonavir, chloroquine, and hydroxychloroquine pills [57]. In the future, it will revolutionize the pharmaceutical industry.

Figure 17 The first 3D-printed drug to receive approval from the U.S. Food and Drug Administration (FDA).

4.7 3D Printed Artificial Lungs:

The product 3D printed artificial lung is a key weapon in the battle against Pulmonary diseases. The tool is mobile, easily deployable and inexpensive but we should take into the consider medical issues related to it. The Pulmonary disease, Acute Respiratory Distress Syndrome affects more than 190,000 people in the USA. While Chronic Obstructive Pulmonary disease affects 5% of the Adult population and 16% of the Veteran population of the USA. Biomedical Engineer Joseph Potkay has developed a 3D printed artificial lung which provide the respiratory support, improved gas exchange, portability, allows lung to heal while patient rehabilitates and biocompatibility. The 3D printed artificial lung functions similarly to natural lungs by removing CO2 and adding O2 to the blood [58].

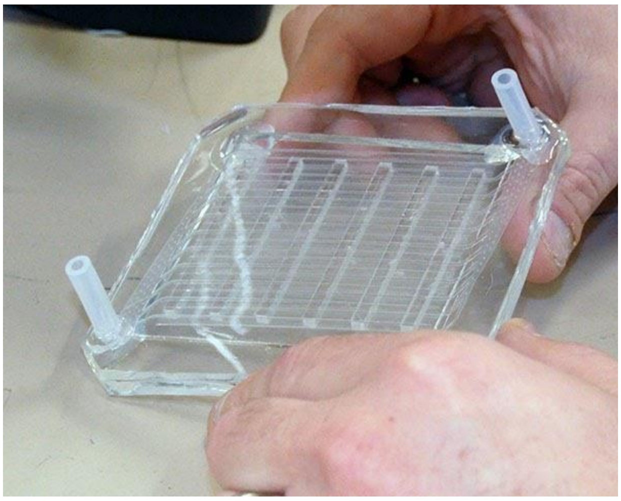

Figure 18 3D Printed artificial lung for treating lung disease [58]

5. Discussion and Challenges

Digital technologies including design and manufacturing by employing DfAM and AM have the capability of providing better solutions during disasters such as the COVID-19 pandemic and post-COVID era. These digital technologies can assist in mitigating the effects of a pandemic by providing a flexible working environment, digital manufacturing of life saving and other daily life equipment, and even robotic based treatment of severely affected patients in order to reduce the risk of medical doctors' lives. Digital manufacturing along with the digital supply chain can provide the necessary equipment even during the lockdown. In addition, cloud based digital design and modeling software will be able to store crucial data that can be useful in similar disasters in the future [9].

As the global COVID-19 pandemic is still unfolding, the demand for protective equipment, detection reagents, and antiviral drugs far exceeds the production capacity of suppliers during this period. From the survey conducted (see Figure 19) in the peak days of the pandemic in the USA, almost 60% of the medical institution did not have a supply remaining for less than a week of N-95 Masks which shows how worse the situation has become. Also, 90% of the organizations have less than two-week supply of Personal Protective Equipment (PPE) [59]. The medical workers who are in the frontline of this pandemic working day in and day out did not have the proper equipment to keep themselves protected. They are already putting their lives in danger we cannot overburden them more.

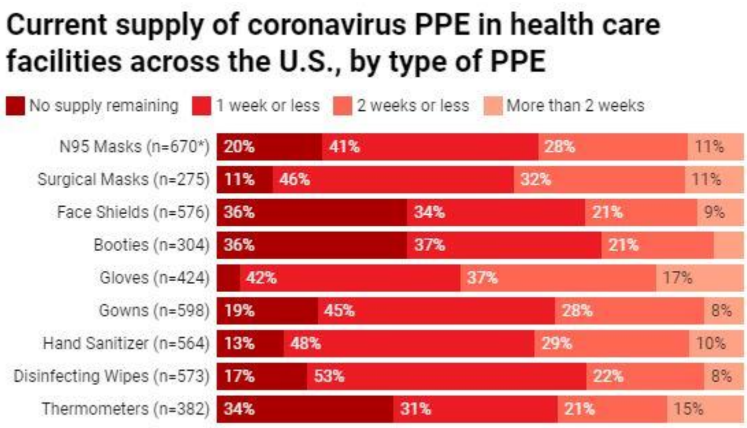

Figure 20 A total of 978 facilities responded to the survey. The "n" for each category refers to the number of facilities that addressed that particular question in their survey response [59]

The medical staff did not have enough required masks, face shields etc. while dealing with the patients. For facing the crisis, 3D printing technologies [60] have seen many innovations in the medical field, contributing to prevent the spread of the COVID-19 virus. In terms of testing kits, numerous 3D-printer manufacturers and organizations are developing throat swabs using different types of flexible polymer materials through 3D printing technologies. The tip of the throat swabs [41] with a complex textured pattern determined by the surgeon was designed by computer-aided design software and finally made by a 3D printer (Figure 12).

The virus outbreaks lead to the supply chain eruption of almost all the items. Hence, the demand for each item has become higher as compared to supply. There arose a problem that people required items, things, and accessories to run their homes. Traditional manufacturing and traditional supply chain are not capable to fulfill the supply issues; therefore 3D printing enabled firms can solve supply chain issues instead of waiting for the products from other countries. For example, in the US, automotive firms are getting contracts for the fabrication of ventilators.

Regarding Medications, unlike the current "one-size-fits-all" drugs, 3D-printed new drugs [61] can create a combination of controlled doses and provide release rate control (immediate release or sustained release) to meet the personalized needs of infected patients (Figure 20). Due to the rapidly changing of the current COVID-19 crisis, the key to responding to a future crisis is to match 3D printing with market demand, as well as speed up production capacity rapidly and carry out enterprise transformation under the premise of product quality assurance.

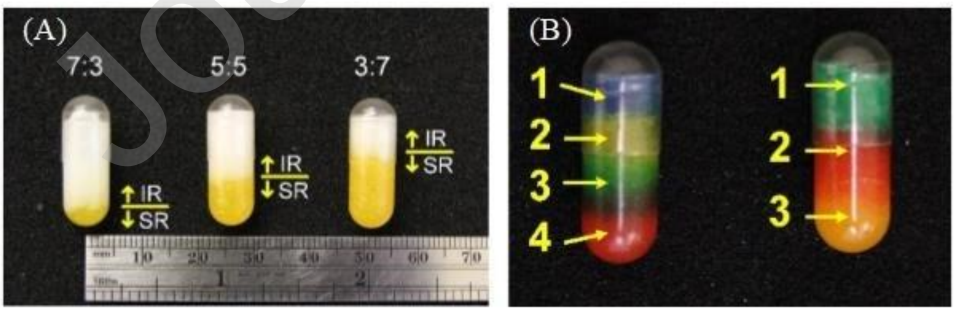

Figure 19 3D-printed capsules: (A) mixed capsules with different ratio of immediate release (white) and sustained release (yellow), (B) layered capsules with different drug compositions [61]

During the pandemic, one of the critical need is to provide quarantine/isolation space for a large number of population. Construction of such spaces in a very short time is a big challenge if traditional ways of construction are employed. Therefore, 3D printing has necessitated making strides for the construction of such emergency spaces. Winsun, an architectural 3D printing company of china has manufactured portable isolation room in only two hours (15 rooms per day) and have installed 15 rooms at the Xianning Central hospital [62]. These rooms were printed using concrete and recycled solid waste and have passed the environmental impact tests.

3D Printed drones can be employed as an alternative of human particularly during disasters such as pandemic to perform many important duties such as medicine and medical equipment delivery, enforce and monitor lockdowns, monitor body temperature of people and initiating public awareness campaigns accordingly, monitor and ensure the law and order during the pandemic situations. Many countries particularly in the middle east have been employed 3D printed drones for aforementioned objectives.

However, there are many aspects in which digital fabrication using AM/3D printing can be beneficial, there are significant flaws in the implementation of direct digital manufacturing. First, preprocessing and post-processing for AM needs to be integrated with 3D printing process to minimize user intervention. Second, a cloud based open access platform needs to be developed where all digital models are stored that are critical for disaster situations. Third and most important is that the AM should be integrated with artificial intelligence (AI) and deep learning in order to study the situation quickly and come up with a solution quickly. The scope of 3D printing is still limited and confined to some extent. As the technological advancement occurs, we are looking for better opportunities to gain full optimization of 3D technology [63,64].

6. Concluding Remarks

Direct Digital Manufacturing (DDM) using AM have a major impact on how entire industries – and consequently, society as a whole – designs and develops various products, builds objects ranging from a small tabletop figure to an entire house, maintain supply chains at various levels, and how to leave conventional manufacturing lines for more exciting avenues. The new ara of additive manufacturing has been quite disruptive. Now, one can scan/computer aided design a part you require write from your laptop. It can be printed from a desktop printer or can be send to the cloud services solution for 3D printing; cloud based 3D printing services with determine your application and requirement and advise you the best type of technology for 3D printing along with the estimated cost; the 3D printed part is printed and send to the customer.

The parts build through DDM are lightweight and produced through the least number of parts, also provide the least maintenance cost. It allows us to build customized products with complex shapes according to customer preferences. The iteration process for the product becomes much easier and faster through 3D printing, the faster the iteration process can be, the more successful products will be delivered to those in need.

This procedure is now adopted by many 3D printing services especially for industrial printers and metal 3D printers with high cost. The printed part quality is good enough to be used in a commerical product. The procedure have dramitically reduced the cost and time on printing a customized part for small and medium quantity item. And we have seen how it all came together in this time of crisis to fill in the need for lack of equipment made way for developing new products and uses, prevented supply chains from collapsing and made industries innovate in developing new products. If the same pace of progress can be maintained, AM technologies will ensure that we be ready to combat the next virulent global pandemic. We observe that 3D printing together with smart CAD design show promise to overcome the disruption caused by the lockdown of classical manufacturing units specially for medical and testing equipment, and protective gears.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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