The Empowering Role of 3D Printing in Responding to the Pandemic: An Analysis

Muhammad Zaheer Abbas*

Abstract

3D printing is well-suited to address the shortage of critical materials in a health emergency because of its potential to swiftly produce customized and cost-effective products locally without requiring expensive infrastructure and specialized skills. This article undertakes an analysis of the role of two different actors – i.e., common citizens and the public sector – in terms of their use of 3D printing in response to COVID-19 with a key focus on how to make more efficient use of 3D printing to deal with future emergencies. The analysis in this study, in respect of the empowering role of 3D printing in responding to the health emergency, draws upon a wide range of sources which include peer-reviewed journal articles, media reports, real-world examples, quotations from stakeholders, and blogs. The findings demonstrate that there is a need for a more systematic, organized, and inclusive approach to fully leverage the use of 3D printing when dealing with a future health emergency. Concerted policy efforts must be made at the global level to bridge the digital divide between low- and middle-income and high-income countries to empower a tremendous amount of human capital to use 3D printing for the common good of humanity.

***Keywords**:* additive manufacturing, COVID-19, Coronavirus, 3D printing, the maker community

Introduction

The COVID-19 health crisis critically strained global healthcare systems and put a spotlight on the significance of 3D printing technology. Additive manufacturing or 3D printing denotes 'any process of creating a physical object through the continual addition of layers of material – in contrast with conventional manufacturing processes in which physical shapes emerge either by removing material, as in machining or changing the shape of a set volume of material' (Schwab and Davis, 2018, p. 142). The health emergency highlighted the potentials of 3D printing to include a wide range of human capital in solving collective problems. By empowering the participation of common citizens, 3D printing plays a key role in expanding the scope of inventive activity and the scale of production.

*PhD, Queensland University of Technology, Brisbane, Australia. ORCID ID: https://orcid.org/0000-0002-8301-885X, Scopus Author ID: 56520969300, **Email address:**muhammadzaheer.abbas@connect.qut.edu.au

This article highlights the uses of 3D printing during the pandemic with a key focus on how to make a more organized and more sustainable use of 3D printing to deal with future emergencies. The approach of this article is to analyse, through the lens of the current COVID-19 crisis, 3D printing's empowering and enabling role to engage a wide range of human capital in addressing the challenges faced by the global community. It analyses the role of two different actors – i.e., common citizens and the public sector – in terms of their uses of 3D printing in response to the pandemic. Part II of this article evaluates community 3D printing and argues that 3D printing is well-suited to empower community participation because its infrastructural costs are low, and it does not require specialized knowledge or skills. Part III examines the public sector's use of 3D printing in tackling with the health emergency. The conclusion in Part IV calls for 3D printing's more efficient, organized, and inclusive use in order to leverage its optimal potential. It also calls for bridging the digital divide between low- and middle-income and high-income countries to make optimal use of 3D printing's unique capabilities for a global impact.

Community 3D Printing in Response to COVID-19

Collaboration between stakeholders is key to saving lives by bringing about rapid adaptation to emerging situations (Advincula et al., 2020). In the current pandemic context, '3D printing appears as a unifying object that connects different stakeholder communities in new ways' (Mahr and Dickel, 2020, p. 716). Efficient use of the Internet provides several options to connect stakeholders. To communicate their needs, hospitals and healthcare organizations can make use of online platforms like public Google Sheets, Twitter, and Facebook. Knowing their specific needs, communities of 3D makers can respond more meaningfully. Free or low-cost access to digital files, for replicating and improving designs, further contributes to strengthening the local networks of the maker community.[1] Because of the widespread availability of the Internet, sharing digital designs through several online platforms is easier than ever before. As rightly noted by Hugo da Silva, 'value chain collaboration is a must. The 3D printing industry was able to respond very fast when the COVID-19 pandemic disrupted the traditional supply chains, as its digitally distributed way of manufacturing allows for creating solutions where the demand is highest' (Langnau, 2020).

Conventional manufacturing methods require large knowledge-base and relevant expertise in professional designing and manufacturing engineering (Trivedi et al., 2018). Skilled professionals are required to design products, set up production, and operate numerically controlled cutting machines (Dickinson, 2018). The three commonly used methods to make solid objects are: 'cutting shapes out of a block of material; adding material piecemeal to build up shapes; and forming material that is liquid or plastic into the required shapes that then set' Bradshaw et al. 2010, p. 6). None of these methods is as simple as 3D printing.

A user of 3D printing technology needs to understand printing materials, 3D printers, the basic mechanisms of 3D printing methods, and the basic details of digital designing (Trivedi et al., 2018). From the comfort of one's desktop, anyone familiar with 3D modelling can create digital designs without needing the prior knowledge, skills, or equipment traditionally required to create professional designs. The reverse engineering and modification of an existing design do not involve a very high level of knowledge and skills (Irfan et al., 2020). One does not need to spend years or even months learning how to create or modify 3D printable designs. The basic functions of 3D modelling programs, like Tinkercad, can be learned within hours. To help interested people learn about 3D modelling, free tools are widely available and accessible.

Private individuals, with no specialized knowledge and experience in manufacturing engineering, can potentially engage in 3D printing products. To have a functioning ecosystem, all they need is the digital file that they are going to print, the 3D printer, and printing material. 3D printers are quite easy to operate. One does not need to be a technician or a skilled expert to adjust and calibrate 3D printers. The manufacturing process, which is automatically controlled from a digital model of the required shape, is safe and hassle-free. Unlike in subtractive manufacturing, nothing is coming off the equipment. The users do not need to be concerned about how to keep their eyes, hands and fingers safe or how to keep themselves shielded from the smoke, fumes and ultra-violet light as 3D printing requires minimal human interventions during the production process.

Leveraging the exceptional abilities of 3D printing, several spontaneous community efforts were initiated in response to the health emergency. The most notable collaborative initiatives – like 'Maker vs. Virus', 'Hack the Pandemic', 'Get Us PPE', and 'Unite4COVID' - are briefly touched upon in this section. Most of these collaborative efforts were motivated by similar concerns and adopted roughly similar approaches to connect those in need of help with those willing and able to help. These initiatives are important because well-coordinated collaborative efforts in response to organized communication between a hospital's supply chain and the 3D printing community are critical to tackling a health emergency.

'Maker vs. Virus' is a Germany-wide humanitarian initiative to bring makers and makerspaces who can produce equipment or spare parts together with people or organizations who need them (Fauth, 2020). It helps the helpers join together in a self-organized manner to deliver a coordinated response as a robust community of makers. Its website provides a list of hubs across Germany so that makers can find a suitable hub near them to keep logistics and transport as simple as possible. A hub is an association of makers which manages and coordinates the central distribution of articles self-produced and contributed by makers.

The 'Hack the Pandemic' project was started in March 2020 by Jerry Orans, a high-school student from New York, to facilitate the creation and distribution of crowdsourced medical supplies. As noted by the founder of the project, 'There are so many projects that Makers and Engineers can help with across the world. Because of this, I have decided to pivot our mission from creating PPE for healthcare workers to working as a rapid recovery group for crises across the U.S. and possibly the world' (Hacking the Panadamic, 2020). Jerry's volunteer efforts focused on using the potential of 3D printing to combat the pandemic: 'We realized that there are people sitting at home with 3D printers and aren't using them for anything. There was our solution, to utilize the unused printers to create much-needed supplies' (Scott, 2020).

The 'Get Us PPE' initiative was launched in March 2020 as a platform for community action. It aimed at urgently providing life-saving PPE free of cost to under-resourced communities. Guided by values - like equity, integrity, compassion, community, innovation, and adaptability – this grassroots movement unites the maker community to share ideas and 3D printing capacity to facilitate the safe and efficient delivery of medical supplies (Get Us PPE, 2020). It allows organizations and hospitals to register their needs for PPE and empowers concerned citizens to meet that demand by donating within their communities (Bala et al., 2022, p. 1).

'Unite4COVID', launched by Royal DSM in May 2020, brings together users of 3D printing by serving as a forum and collaborative hub where healthcare workers can request parts and manufacturers can respond by sharing ideas and capacity (Langnau, 2020). It creates an open collaborative development community space and helps in speeding up the development process by collecting and coordinating the needs and requests of healthcare professionals, bringing together solution providers and tracking progress. As noted by the Vice President of Royal DSM Additive Manufacturing, 'By bringing together organizations with different manufacturing competencies and matching them with the needs of the organizations in vital sectors, we can offer effective solutions more quickly' (Langnau, 2020).

In the United Kingdom, a community of 3D printing volunteers '3DCrowdUK' was formed in March 2020 to supplement the traditional PPE supply chains (COE-EDP, 2020). In a short time, it brought together more than 8,000 volunteers to print, assemble and distribute face shields on a priority basis (Hospital Hub, 2021). The community organization helped frontline healthcare workers across the UK by delivering 200,000 face shields to the National Health Service within four months of its formation (COE-EDP, 2020). 3D printing played a central role in this success story by enabling community volunteers to step forward and support this endeavour to solve a real-world problem incredibly quickly.

In Pakistan, a team of researchers at the Aga Khan University, led by Saleem Sayani, used 3D printing to develop a prototype of nasal swabs. This public-spirited initiative of AKU helped Pakistan deal with supply constraints at the peak of the pandemic as the AKU 3D printer was able to produce more than 1,000 nasal swabs per day at a significantly lower price as compared to the swabs that Pakistan was importing to combat the pandemic (Aga Khan University, 2021). Another initiative in Pakistan was taken by a group of volunteers to 3D print ventilators. This group called 'Pakistan Against COVID19-Volunteers' comprised biomedical professionals, doctors, engineers, academics, and resource mobilisers (Ahmad, 2020).

3D printing enables improved collaboration and coordination between the maker community and the 3D printing industry. Community participation can complement or augment industry efforts. For instance, Formlabs, a Boston-based 3D printing company, initially used its 250 printers to produce around 100,000 diagnostic nasal swabs per day (Royal DSM, 2020). Then Formlabs decided to mobilize its community of users to quickly mass-produce the swabs. The deployment of nearly 1,000 printers significantly enhanced the per-day production capacity. It is estimated that more than 25 million swabs have been 3D printed across the globe and many more are actively being produced (Ford et al., 2020).

There have been several notable individual contributions from concerned community members. Quinn Callander, a 12-year-old Boy Scout from Canada, helped medical professionals by 3D-printing tension relief mask adjusters. Mask adjusters are handy in making face masks more comfortable to wear (Evans, 2020). They 'clip onto the straps of face masks and are placed against the back of the head to raise the straps above the ears, eliminating irritation' by taking the pressure off the wearer's ears (Wilson, 2020). This is an impactful contribution as many frontline healthcare professionals need to wear masks for longer periods. Wearing masks for a long time can be quite uncomfortable for their face and ears (Vincent, 2020). Many medical personnel face issues like nagging and uncomfortable chafing around the ears because of wearing masks for extended periods. As noted by a 3D printing specialist, 'we were seeing reports of nurses' faces being cut and bruised by their existing protective equipment. Our frontline workers are battling enough already, without having to tend to sore and swollen faces at the end of a 12-hour shift' (Dickin, 2020). Quinn helped various hospitals by donating hundreds of 3D-printed mask adjusters. Anyone having a 3D printer can print the design of the mask adjuster as it is available in the public domain (Wilson, 2020). Due to limited complexity and size, mask adjusters can be produced quickly in a variety of different materials (Manero et al., 2020). Quinn's valuable contribution, to support medical workers, highlights the potential of 3D printing to create inspirational stories of local heroism by engaging and empowering creative members of the global community.

In Italy, a local hospital was faced with the shortages of venturi valves (Mahr and Dickel, 2020). To deliver oxygen at a variable concentration, a venturi valve connects the patient's face mask to breathing machines. is one of the key components of a ventilator, which is required to. As the demand for ventilators was exceptionally high during the pandemic, there were shortages of venturi valves. To address shortages, two concerned citizens Alessandro Romaioli and Cristian Fracassi decided to help the hospital (Nazir et al., 2021). After studying the valve for few hours, the duo created a valve prototype and 3D-printed replacement valves (Tino et al., 2020). They supplied valves for more than 100 ventilators to the local hospital in less than 24 hours (Contreras, 2020).

Because of its simplicity and low cost of enabling technologies, 3D printing empowers concerned members of the community to practically solve a lot of real-world problems by turning their unique ideas into innovative objects. Concerned community members may be full of ideas to solve problems or address unmet needs, but they lack training and skills in traditional manufacturing methods to turn their ideas into useful products. They do not need to be product development experts to materialise their innovative ideas by using 3D printing tools. 3D printing facilitates collaborative human effort to address common problems. It allows people to put their knowledge and experience together to deliver a quick solution (Zhang, 2020). As noted by an author, 'giving people the ability to make things for themselves can be the fastest way to solve their problems' (Mandavilli, 2006, p. 862).

Because of its low infrastructural needs, almost no prior-knowledge requirements, and affordable availability of enabling technology, 3D printing empowers common citizens to play an active collaborative role to not only find solutions to emerging problems but also address supply-chain gaps. To become part of the citizen supply chain, one does not need to have a large production facility. Anyone who possesses a 3D printer can potentially contribute on a personal level. 3D printers are like portable factories which can convert hobby rooms into manufacturing hubs for 3D printable goods. People can contribute to supply-chain working out from the comfort of their homes by sparing very little amount of time. It takes only a few minutes to set up for a print and one can do other things while the printer runs on its own until the printing job is finished. These individual contributions may appear too small, but the overall positive impact of community-level fabrication to augment government efforts can be notable. A little bit of effort from everyone can help in a community emergency response. 3D printing, which enables community participation by integrating consumers into the supply chain, is rapidly becoming democratized (Vordos et al., 2020).[2]

The overall cost of enabling technology is further dropping over time. The price of acquiring a 3D printer has decreased dramatically in recent years. The cheapest 3D printer costs about USD 320 only (Rajam and Jha, 2018). The cost of the consumer-ready materials commonly used in 3D printing is easily affordable. Until recently, 3D scanners were quite expensive. The price of acquiring a reasonable 3D scanner has dropped to below USD 250 only (Valdivieso, 2020). Smartphones can be used to perform 3D scanning with the help of applications like the Bellus3D FaceApp or 123D Catch (Autodesk, 2020). 3D modelling can be done by using a free or low-cost design program, like Tinkercad,[3] SketchUp,[4] or Fusion 360.[5] These design programs are becoming easier to use (Mundhra, 2020). If one does not have access to a 3D scanner or a 3D modelling design program, digital designs are available from free or affordable online platforms like Thing verse, Grab CAD, You Magine, MyMiniFactory, Shapeways and many more. It is only because of 3D printing technology that, by spending less than a thousand dollars, one can have the capability to transform ideas into physical objects that were once in the hands of very few.

It is, however, important to note that the common and cheap 3D printers used by community members are plastic or resin desktop machines. These low-end printers are constrained in their capabilities to produce a wide range of good quality products with reliable accuracy and durability. The poor printing quality of desktop printers is a concern, especially when these machines are used to print medical equipment. The mechanical properties of 3D printed parts can be reduced because of failures resulting from the limited adhesion between layers. There can be large porosities in the printed part, which can lead to significant challenges regarding durability (Manero et al., 2020). These porous 3D-printed parts tend to harbour microbes (Tarfaoui et al., 2020). This porosity is particularly problematic when coupled with low-temperature resistance of printed parts. Polylactic Acid filament, generally used as a printing material for low-end 3D printing, has a drawback in terms of temperature resistance as it starts softening at 50°C (Mueller et al., 2020). Products fabricated from this material are not suitable for temperature-based UV light sterilization processes (Armijo et al., 2021).

To fabricate high-quality medical products in a future health emergency, community members will need access to advanced 3D printers. The more industrial species of 3D printers are still expensive. Purchasing a personal 3D printer capable of printing high-quality products with metal, fiberglass, or carbon fibre is not an affordable option for consumers or community members. The materials used by these industrial-scale 3D printers are also expensive (Birtchnell and Urry, 2016). It is important to mitigate these access barriers. While individual access to advanced 3D printers seems problematic and unrealistic, communal or shared access can be a viable option.

Fablabs or fabrication laboratories practically implement the idea of infrastructure sharing. Fablabs have an important role in enabling the participation of those community members who cannot afford to buy a personal 3D printer and/ or other enabling technologies. Fablabs, also known as maker spaces, facilitate problem-solving activities by providing citizens with a variety of digital fabrication tools coupled with the expertise of mentors. Fablabs enable makers to innovate by taking designs from concept to reality (Scott, 2020). Fablabs have been used to produce eye protectors, visors for protective face masks, face shields, and door openers. Fablabs were instrumental in encouraging technological humanism. As noted by Sherry Lassiter, President and CEO of the Fab Foundation, 'We want everyone to be well-informed and using professional best practices in digital fabrication. This is a unique opportunity to help our communities in important ways, and to demonstrate the potential of digital fabrication, how it brings social impact, and how it supports humanitarian efforts' (Lassiter, 2021).

Working together is the key to the strength of human communities. Fablabs promoted collaborative efforts and empowered community participation. By making their premises, machinery and supporting staff available to the peer-support networks of the maker community, Fablabs have supported COVID-19 relief efforts in powerful and incredible ways. In order to effectively deal with a future pandemic, the world needs more Fablabs - equipped with more advanced technological resources - not only in rich countries but also in developing countries. Such infrastructure sharing for a viable 3D printing ecosystem is critical to leverage the collective intelligence and creativity of the global population to solve a wide range of emerging problems in a future health emergency.

Public Sector Applications of 3D Printing in Response to COVID-19

There was hardly public sector use of 3D printing in response to the pandemic. Governments, especially in developing countries, are arguably not fully aware of the unique significance of 3D printing when dealing with a crisis. Although 3D printing has been extensively used by the maker community to combat shortages of medical equipment during the health emergency, most of governments across the globe failed to make concerted efforts to leverage the full potential of this enabling technology. In most of cases, those who needed help and those who wanted to offer help got connected through online platforms that were not initiated or organized by the public sector.

'America Makes', established by the U.S. government in 2012 as a public-private venture, is a notable example of a government effort to deliver innovative and collaborative 3D manufacturing solutions. 'America Makes' facilitates entry paths for the engagement of the maker community and manufacturing industry insiders with 3D printing capabilities by connecting them with healthcare facilities (Vincent, 2020b). Healthcare providers can easily communicate their immediate needs. To address any specific needs, this platform invites stakeholder participation, under a compressed timeframe, through initiatives, like the 'Fit to Face Challenge'. To connect efforts by making the designs available to manufacturers and healthcare providers, 'America Makes' created an online repository (America Makes, 2020). This initiative is important to leverage existing resources for responsible manufacturing and deployment of 3D-printed medical supplies.

The National Institutes of Health 3D Print Exchange, another public sector initiative, was launched by the U.S. government in 2014. It provides an online tool for people to contribute any bio-scientifically and/ or clinically relevant 3D printable models. The NIH 3D Print Exchange marks crowd-sourced device designs as 'Reviewed for Clinical Use' and makes them easily accessible online after they pass through the Department of Veterans' Affairs clinical evaluation protocols (Vincent, 2020a). The NIH 3D Print Exchange also shares assembly instructions and other instructional information about 3D-printed designs (Schmidt et al., 2020). This already existing public repository for open sharing and open-sourcing of design blueprints in a community-driven environment is an important resource in the context of COVID-19.

Although public sector use of 3D printing in response to COVID-19 was deficient, there are some instances where public sector academic institutions in technologically advanced countries offered innovative solutions to emerging problems. There were shortages of powered air-purifying respirators or PAPRs. Frontline health professional, exposed to higher risks of personal infection in a hazardous environment, need advanced protection in the form of PAPRs to be safe from airborne viral particles (Maracaja et al., 2020). A PAPR may also be warranted in patients who need superior protection against airborne transmission, which is different from droplet transmission. PAPR devices are not only more efficient in protection against hazardous airborne particles but also more comfortable and effective in limiting inadvertent facial touching (Coté et al., 2020). With a limited number of dedicated PAPR units, many hospitals were constrained in caring for a large number of COVID-19 patients. To address these chronic shortages, at the University of Nebraska-Lincoln, clinicians designed a 3D printable adapter to connect a 3M Versaflow air handling unit with a Dover brand Hood (Scherr, 2020). This compatibility between the two systems, enabled by 3D printing, potentially enhanced the PAPR fleet of hospitals. The digital design file to print the adapter is available on request. Traditional manufacturing techniques lack the ability to adapt quickly to respond to emerging needs.

The University of Melbourne, a public sector university in Australia, contributed to addressing a problem related to the use of PAPR devices. Medical professionals using PAPRs face a common problem that their surgical gowns get sucked into the PAPR. Making use of the capabilities of 3D printing, Austin Health, 3DMedLab, and the University of Melbourne collaboratively designed and 3D printed PAPR clips in less than three days (3dMedLab, 2020). This innovative clip, called the spider, effectively addressed this problem. This also exemplifies the cost-cutting role of 3D printing as the cost of fabricating these clips is nominal. This example puts a spotlight on the role of additive manufacturing in enabling public sector universities to come up with innovative approaches to solve problems economically and time-efficiently.

Doctors at the University of South Florida in Tampa and North well Health in New York designed and prototyped 3D printable nasal swabs to address shortages of diagnostic nasal swabs (Zastrow, 2020). Although the concept and design of the 3D printed slides are protected under provisional patents granted to USF Health in March 2020, the patent holder decided to keep the design freely available to slow the spread of the virus by addressing supply chain shortages (Tino et al., 2020). This example highlights one of the most remarkable contributions of medical 3D printing in empowering caregivers and health academics to transform their innovative ideas into physical designs for quick clinical solutions. On the contrary, the conventional typically one-sided industry-caregiver relationship lacks meaningful inputs from caregivers and health academics.

Several other universities used their 3D printing competencies in response to the pandemic. For example, at Grand Valley State University, Applied Medical Device Institute (aMDI) collaborated with Carbon 3D to fabricate face shields and mask bands (Applied Medical Device Institute, 2020). Scientists at King's College London and the University of Birmingham brought together their 3D printing expertise to create customized silicone seals to fit individual faces. The Maker Lab at the University of Illinois collaborated with the surrounding community to design and manufacture 3D-printed face masks, face shields, mask adjusters, and comfort straps (Kotskyy, 2020). A team of engineers from the University of North Texas collaborated to design and 3D print ventilator splitters in the university's digital manufacturing lab (University of North Texas, 2020).

Well-coordinated localized manufacturing in an emergency can be a huge relief for governments. The timely availability of resources is a key consideration when it comes to public health emergency response. The current pandemic exposed the fragility of the globalized industrial supply chains and highlighted the importance of local manufacturing capabilities (Mahr and Dickel, 2020). Even when the availability is not an issue, timely delivery – especially to geographically remote countries – can be an issue because of the imposition of export bans, closed borders, transport restrictions,[6] and logistical issues (Evans, 2020). Because of its special features, 3D printing has the potential to address these challenges by actualizing localized and distributed manufacturing and by reshaping supply chains. It simplifies global supply chains by relocating production to customers and eliminating the role of intermediaries.

3D printing enables fabricating medical equipment and other materials in hospitals (Romeo, 2020). Hospitals are increasingly building on-spot fabrication capabilities by acquiring 3D printers. In advanced countries, many hospitals used their 3D printers to fabricate parts of medical devices (Castellucci, 2020). It is important for governments to provide hospitals with 3D printers to de-risk shortages of materials in an emergency. Such decentralization of manufacturing capabilities is crucial to negate problems caused by exceptionally high demand coupled with disruptions in production and physical transportation of manufactured goods.

The use of 3D printing, to provide local manufacturing solutions, not only shores up supply chains but also reduces the monetary and ecological costs of cross-country or even cross-continent shipping of physical objects. To minimize the costs of production, many medical equipment businesses rely on overseas production in developing countries (Salmi et al., 2020). For instance, over 70% of respiratory protection supplies in the U.S. are produced in China. It is estimated that China produces almost half of the world's face masks (Tarfaoui et al., 2020). Shipping to far-off countries involves substantial costs, delays, and vulnerabilities. In contrast, the distribution of 3D printable digital objects, in the form of CAD files by using online platforms, saves both monetary and natural resources. Governments are relieved of several burdens if digital files shared over the Internet are 3D printed closer to the point of use resulting in shorter, less vulnerable, less costly, and less polluting supply chains.

3D printing is cost-efficient in many ways. The unique ability of 3D printing to make a part or even an entire product in one build allows it to cut costs by eliminating a lot of machines. Unlike any other manufacturing method, 3D printing does away with moulding processes and infrastructural needs such as cutting and casting tools (Rajam and Jha, 2018). In contrast, conventional production processes - involving subtractive or moulding techniques - require substantial investments in tooling, machinery and even robots (Mueller et al., 2020). The high cost of developing traditional moulds poses a financial barrier to concretising and commercialising many innovative ideas (Ballardini et al., 2016).

3D printing cuts costs by reducing material consumption. The material costs of 3D printing are quite low because it uses far less material than conventional subtractive manufacturing methods, which carve out an object from a piece of metal or plastic (Mundhra, 2020). Instead of cutting down an existing solid block of material into a shape, 3D printing starts with a blank slate and builds products by adding layers of material (Cano, 2015). The movement of the print head in three dimensions is guided by a digital design file which is read by the printer's motherboard. In this way, this method of manufacturing creates a minimum or even no waste by-product to limit both financial and environmental costs.

Another way 3D printing reduces cost is by enabling low-volume manufacturing. Making a single product by using this technology can be as cost-effective as making a million products. The same technological infrastructure is used to design and print diverse objects of very different shapes. Variety is free as it does not make much difference, in terms of costs of designing and manufacturing, whether you print a million products that are all different or a million products that are all identical. This unique benefit of 3D designing and manufacturing substantially reduces the cost of failure and enhances the freedom to experiment with multiple designs without worrying about the traditional economies of scale.

Recommendations

To leverage the full potential of 3D printing in a more organized way, governments need to provide infrastructure, services, resources, and support to the 3D innovators and the maker community. 3D makers must be supported logistically so that they can extend their imagination and transform their creative ideas into physical objects without being concerned about budget constraints. Governments should not leave this task to corporatized bureaus because corporate decisions are not necessarily informed by public-interest considerations. Governments may consider establishing 3D printing labs in public sector academic institutions. These purpose-built labs proposed by this study can have a three-fold positive role.

First, the 3D printing tools in these labs will provide engineering and design students with practical exposure to modern concepts of advanced manufacturing. Business students will also benefit from 3D printing labs because 3D printing is changing business models and creating opportunities for entrepreneurs (Abbas, 2022, p.68). It is important for business students to understand this disruptive technology which is having an impact on supply chains, manufacturing, marketing, pricing, warehousing and many other aspects of a business.

Second, universities can generate revenue by using 3D printing tools to materialize their intellectual capital. Universities produce most of the world's intellectual capital (Birtchnell et al., 2017). Having in-house 3D printing capabilities will allow universities to capitalize on this knowledge in order to create wealth by operating more entrepreneurially.

Third, to combat the current and future public health crisis, these labs can serve as a network of public sector facilities to support 3D printing activities logistically and technically. They can provide supervised or technically assisted 3D printing services on a not-for-profit basis or at subsidized rates. They can offer affordable short training courses to community members who are interested in learning or improving 3D modelling, 3D scanning, and product prototyping skills. Personalized tutoring sessions can be offered to those who want to acquire advanced knowledge about 3D printing processes and materials. Such community-empowering or the capacity-building role of 3D printing labs at public sector academic institutions is critical in responding to future health emergencies. Despite their crucial role, 3D printing labs can be rarely found in academic institutions, especially in developing countries. Governments, both in developed and developing countries, need to allocate resources for building fully functional 3D printing labs with a key focus on linking universities with the surrounding 3D maker community. These proposed labs can leverage community connections to serve as networked 3D printing response hubs in a future emergency.

Keeping in view the risks of fabricating medical materials by using low-end desktop printers, it is important to have time-efficient quality control measures in place to ensure compliance with healthcare safety standards. In the U.S., the designs submitted to the online repository created by 'America Makes' are placed on a fast track for review by the Food and Drug Administration, the Department of Veterans' Affairs, and the National Institutes of Health (America Makes, 2020). However, the scope of this arrangement is confined to the U.S. only. There is still a need to start such initiatives in other jurisdictions to ensure the safety of consumers in exploiting 3D printing capabilities. To provide a trusted source of verified designs, the relevant government agencies at national levels need to create an official repository of approved 3D designs that are made available online after making sure that they are functionally suitable for the specific intended purpose, reliable, safe, and durable. Such initiatives at the national will help users in choosing a safe and reliable model for printing the needed medical devices.

Conclusions

Working together is the key to the strength of human communities. Because of its low infrastructural needs, almost no prior-knowledge requirements, and affordable availability of enabling tools, 3D printing empowers the maker community to not only solve a lot of real-world problems in creative ways but also play a collaborative role to address supply-chain gaps in a sustainable manner. Low- and middle-income countries lack 3D printing ecosystem. This deficiency is a formidable barrier to leveraging the creativity and goodwill of a wide range of human capital as billions of people are excluded from digital fabrication. Concerted policy efforts are needed to address the digital divide between low- and middle-income and high-income countries for a more inclusive and consolidated response to a future health emergency.

There were not as many government-initiated efforts to leverage the potential of 3D printing in response to the pandemic. Governments need to be prepared for a more proactive role to ensure a more systematic and organized use of 3D printing in response to a future pandemic. Nevertheless, several public sector universities used their 3D printing capabilities to offer creative solutions to problems resulting from the pandemic. This article calls upon national governments, both in developing and developed countries, to establish 3D printing labs in public sector academic institutions. These purpose-built labs can serve as a network of public sector facilities to support 3D printing activities logistically and technically. These proposed labs can leverage their connections with the surrounding communities to serve as networked 3D printing response hubs in a future public health emergency.

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[1] The maker community comprises makers with diverse interests and skill sets as they come from all walks of life. These makers spread across the globe focus on health, environment, sustainable development, and local culture. The maker community is inspired by the maker movement, which is a cultural trend to enhance the ability of individuals to be creators of things. See more Cole, Brenda (2014) Maker Movement - *TechTarget*. https://www.techtarget.com/searcherp/definition/maker-movement. Accessed 5 Dec 2022

[2] For instance, there is an estimated number of 444,000 personal 3D printers in the U.S. and 168,000 printers in the U.K.

[3] Tinkercad is an easy-to-use online 3D modeling program. It is free of charge and runs in a web browser. See more Valdivieso, Carlota (2021) Tinkercad: The Onlie Software to Start 3D Modeling - *3Dnatives*. https://www.3dnatives.com/en/tinkercad-all-you-need-to-know-120320204/#!. Accessed 5 Dec 2022

[4] SketchUp is a program for a broad range of drawing and design applications. SketchUp users may upload and download 3D models from 3D Warehouse, which is an open library. See more https://3dwarehouse.sketchup.com/?hl=en. Accessed 5 Dec 2022

[5] Fusion 360, developed by Autodesk, is a commercial design software application. This application has built-in capabilities to do 3D modeling. See more https://www.autodesk.com/products/fusion-360/overview?term=1-YEAR&tab=subscription. Accessed 5 Dec 2022

[6] To curb the spread of COVID-19, more than 7 million flights have been cancelled worldwide. Even several cargo flights were cancelled which adversely impacted the delivery of much-needed medical equipment.