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3D Printing in COVID-19: Productivity Estimation of the Most Promising Open Source Solutions in Emergency Situations

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Abstract: The COVID-19 pandemic has caused a surge of demand for medical supplies and spare parts, which has put pressure on the manufacturing sector. As a result, 3D printing communities and companies are currently operating to ease the breakdown in the medical supply chain. If no parts are available, 3D printing can potentially be used to produce time-critical parts on demand such as nasal swabs, face shields, respirators, and spares for ventilators. A structured search using online sources and feedback from key experts in the 3D printing area was applied to highlight critical issues and to suggest potential solutions. The prescribed outcomes were estimated in terms of cost and productivity at a small and large scale. This study analyzes the number and costs of parts that can be manufactured with a single machine within 24 h. It extrapolates this potential with the number of identical 3D printers in the world to estimate the global potential that can help practitioners, frontline workers, and those most vulnerable during the pandemic. It also proposes alternative 3D printing processes and materials that can be applicable. This new unregulated supply chain has also opened new questions concerning medical certification and Intellectual property rights (IPR). There is also a pressing need to develop new standards for 3D printing of medical parts for the current pandemic, and to ensure better national resilience.

Keywords: coronavirus; additive manufacturing; rapid manufacturing; COVID-19; SARS-CoV-2; 3D printing; supply chain disruption; production; bridge manufacturing; PPE

1. Introduction

The COVID-19 pandemic has illustrated the vulnerability of conventional global supply chains. Over the past decade, other major disruptions have also exposed this vulnerability [1,2]. For example, the eruption of an Icelandic volcano in 2010 affected time-critical air shipments [3]. The Japanese earthquake and tsunami in 2011 caused several months of disruption in the automotive industry [4]. Thailand's 2011 floods had a huge impact on the supply chains of computer manufacturers in need of hard disks drives [5]. After Hurricane Harvey in 2017, there was a mass disruption in the U.S. chemical production, which caused shortages of essential industrial building materials [6]. The avian influenza A (H5N1) affected trading and transportation systems in major cities, and caused a destructive effect

on global food supply and business operation [7]. The coronavirus disease (COVID-19) pandemic has once again demonstrated the fragility of conventional global supply chains. Cost minimization and cost-cutting measures are the most significant drivers that lead to fragility and vulnerability of global supply chains [7,8]. To date, a plethora of medical equipment businesses are relying on overseas production in developing countries to minimize costs. This has led to shortages in the supply of much-needed medical and non-medical products required to fight the COVID-19 pandemic. As a result, there is an unprecedented shortage of personal protective equipment (PPE) for healthcare workers, lack of ventilators and spare parts for patients, insufficient supply of sanitizer solutions, and scarcity of coronavirus test kits for the general public. Countries that are affected have imposed bans on the export of PPE and other products critical for health. These bans have subsequently caused a greater disruption of medical supplies, and illustrate the vulnerability of global supplies and logistics amid a large upheaval from the pandemic.

Over the past decade, 3D printing (additive manufacturing) has been increasingly implemented in the medical industry. For example, medical and preoperative models [9], surgical implants [10–13], and tools and templates for operations [14] have been fabricated using 3D printing. Major advantages of 3D printing are its ability to offer mass customization, to produce freeform parts on demand, and to cater to lot size indifference and other patient-specific designs [15–17]. In the current COVID-19 pandemic, 3D printing has been increasingly used to print spare parts for medical devices and protective gear, due to the unavailability of supplies. According to the search volume data of Google, the term "3D printing" was searched 2.2 times more in April 2020 than in the same period last year. Key benefits of 3D printing over conventional manufacturing are faster production, digital storage and traceability of part files, reduction in delivery time, and the ability to produce components regardless of the complexity of part geometry [18,19].

To date, there are only a few publications related to COVID-19 and 3D printing. More specifically, the following six topics have been investigated: open source ventilators [20], connectors for breathing devices [21], sourcing PPE [22], pressure-regulated ventilator splitting spare parts [23], respirators [24], and 3D printed ventilator parts [25]. Thus, there is reason to believe that the productivity of 3D printing with regard to the COVID-19 pandemic is not fully understood. The aim of this paper is to investigate the productivity of the most promising open source 3D printing solutions for the COVID-19 pandemic.

2. Materials and Methods

2.1. Gathering the Most Promising Open Source Solutions

An overview of 3D printers and resulting products used in the COVID-19 pandemic was undertaken using multiple sources including, but not limited to, local newsletters, national government press releases, social media, 3D printing newsletters, university and company webpages, and other professional networks. Based on the collected data, the authors performed a clustering method and selected the most popular and potential products and devices (Table 1) currently used in the COVID-19 pandemic. The selection process was limited to open source parts.

2.2. 3D Printing and Cost Model

Three ISO/ASTM 3D printing processes, namely vat photopolymerization (VP), material extrusion (ME), and powder bed fusion (PBF), are most commonly used to produce parts in the COVID-19 pandemic. The ME process is the most widespread 3D printing technology to date. The VP process is widely used in the medical field to print biocompatible materials. The PBF process is broadly used for producing functional prototypes, end-use parts, and rapid tooling. Table 2 lists the 3D printing machines and materials that are currently being used, or that can otherwise maintain the functional integrity of the respective products. Further, alternative materials can also be used as stated in Table 2.

Table 1. Products currently being manufactured using 3D printing in the COVID-19 pandemic.

Description	Users	Pandemic Demand	3D Model Source
Face mask (filter is attached separately)	Frontline workers: hospital staff, paramedics, law enforcement authorities, etc.—individual people	Very high > 10 billion	https://amaskforall.com/
Face shield (3D printed holder)	Frontline workers: hospital staff, paramedics, law enforcement authorities, etc.—some individual people	Very high > 1 billion	https://www.prusaprinters.org/prints/25857-prusa-face-shield https://www.3dsystems.com/covid-19-response#faceShield
Nasal swab	Hospital staff, paramedics, law enforcement authorities, etc.—every person to be tested	Very high > 100 million	https://usf.app.box.com/s/wxmlj0r66vp8bzei6o7sur1kq1jr8o1i/folder/109236323102
Venturi valve	Hospitals—shortage of parts	Medium > 10 million	https://grabcad.com/library/respirator-free-reanimation-venturi-s-valve-1/details?folder_id=8017467

Table 2. 3D Printing technologies and alternatives.

ISO/ASTM Technology Class	Equipment & Material	Layer Thickness	Notes	Sterilization	Alternatives
VAT Photopolymerization	Form 2™ & Dental SG. (Formlabs Inc., USA)	0.1 mm	Biocompatible material, needs post-curing and autoclaving	Autoclave	Vat photopolymerization technologies with material approved for medical use
Material Extrusion	uPrint™ SE Plus & ABS (Stratasys Ltd., Israel)	0.33 mm	Material not medically approved, product might not be airtight	Isopropyl alcohol	Other material extrusion equipment and materials, approved material would be beneficial
	Ultimaker™ 2 & ABS (Ultimaker BV, Dutch)	0.1 mm	Material not medically approved, product might not be airtight		
Powder Bed Fusion	3DSystems™ ProX SLS 500 & DuraFormProX PA (3D Systems Inc., USA)	0.1 mm	Biocompatible material	Autoclave	Powder bed fusion technologies with approved material for medical use

The build volume of the respective 3D printing machines is often packed/nested in a manner that aims to fully maximize the number of parts within the build area, while maintaining a high probability of a successful print. Though the productivity may be improved by completely packing/nesting the build volume with different types of products in one batch to increase packing density, particularly in the PBF process, this study focuses on identical products to fully pack the build volume for simplicity.

The pre-processing software of different 3D printing processes have an unidentical array of control settings and build parameters, owing to different materials and fusing mechanisms. In principle, a higher layer thickness than the one used in this study may be selected to manufacture the prescribed parts, which would also decrease the print time per batch. However, parts manufactured with an increased layer thickness can yield relatively lower quality and weaker strength. To this end, this study employs standardized 3D printing parameters for both build and support structures prescribed by the original equipment manufacturer (OEM), to confirm process assurance and repeatability of results. The supports were generated using OEM algorithms for the certified material profiles.

Figure 1 shows the packing arrangements of products in different build volumes that enable a good build solution. For example, the nasal swabs intended to be manufactured through the PBF process were not stacked over each other, because the consecutive addition of such a long and narrow geometry would increase the risk of an unsuccessful end result in the build. This research opts for a more pragmatic approach, in which the main focus is on the 3D printing process itself, and the in-depth analyses for post-processing steps, sterilization, and cost of delivery are largely simplified.

A cost model with five components was used in this research. The 3D printing machine and its maintenance, raw material, labor, overhead, and sterilization are the basic cost components. By employing this model, we estimated the cost of producing and sterilizing four exemplar medical parts, namely face masks, nasal swabs, face shield holders, and Venturi valves, using four 3D printing machines with different raw materials and varying batch sizes. Different batch sizes for an identical 3D printing machine have also been selected, to highlight the effect of batch size on the costs related to the pre- and post-processing. In total, 17 experiments were conducted. The setting of the experiments, the data, and the assumptions used to create the cost models are presented in Tables 3–5. Data regarding the build times and material consumptions for the experiments was extracted from the OEM software of the 3D printing machines, because this was the most accessible means of data. The software were PreForm 2.20.0, GrabCAD 1.40.28.60898, Ultimaker Cura 4.5.0, and 3DSprint 2.13.0 for Form 2™, uPrint™ SE Plus, Ultimaker™ 2, and 3DSystems™ ProX SLS 500, respectively.

The assumptions regarding the cost of procuring the 3D printing machine and the estimated annual maintenance are presented in Table 4. Moreover, the hourly labor cost for the pre- and post-processing of the print job was assumed to be 15 € at a minimum hourly wage, and the duration of labor requirement for each print job was estimated through expert opinion. The cost and method of sterilization was extracted from the literature for the 17 experiments, as shown in Table 5. Parts produced from Dental SG and Polyamide 12 can be sterilized by an autoclave, while the ABS parts require submersion in a C3H8O [26] solution.

Table 3. Experiment settings and model parameters.

Exp. ID	Product	Equipment	Material	Capacity of Machine Chamber (L)	Experiment Batch Size	Print Time/Batch (h)
1	Nasal swab	Formlabs Form 2	Dental SG	2.58	400	12.27
2		3DSystems ProX SLS 500	PA12	57.46	3254	37.98
3	Venturi valve	Formlabs Form 2	Dental SG	2.58	18	8.03
4		3DSystems ProX SLS 500	PA12	57.46	625	54.70
5		Ultimaker 2	ABS	10.19	1	2.27
6				10.19	47	108.45
7		uPrint SE Plus		6.26	24	33.75
8	Face mask + lid	Formlabs Form 2	Dental SG	2.58	1	3.92
9		3DSystems ProX SLS 500	PA12	57.46	120	36.65
10		Ultimaker 2	ABS	10.19	2	19.62
11				10.19	18	195.65
12		uPrint SE Plus		6.26	2	12.27
13	Face shield holder	3DSystems ProX SLS 500	PA12	57.46	88	38.00
14		Ultimaker 2	ABS	10.19	1	6.85
15				10.19	10	76.35
16		uPrint SE Plus		6.26	1	3.48
17	Face shield holder SLS optimized	3DSystems ProX SLS 500	PA12	57.46	374	102.52

Table 4. Cost model estimates.

Exp. ID	Material per Build	Support Material Volume	Material Cost	Cost of 3D Printer (k€)	Expected Lifespan of 3D Printer (years)	3D Printer Maintenance (Annual Cost in k€)	Labor Cost per Hour (€)	Labor Required per 3D Printer (Person Hour per Run)
1	224 ml	Not needed	270 €/l	2.7	3	0.5	15	2
2	40.06 l		13.5 €/l	350	10	10		8
3	167 ml	Included in the build	270 €/l	2.7	3	0.5		2
4	49.64 l	Not needed	13.5 €/l	350	10	10		5
5	9 g	1 g	0.06 €/g	1.9	2	0.4		0.5
6	412 g	44 g		1.9	2	0.4		2
7	197 cm ³	107 cm ³	0.29 €/cm ³	16	8	1		1
8	70 ml	Included in the build	270 €/l	2.7	3	0.5		1.5
9	54.23 l	Not needed	13.5 €/l	350	10	10		4
10	90 g	8 g	0.06 €/g	1.9	2	0.4		0.5
11	780 g	185 g		1.9	2	0.4		1.5
12	136 cm ³	35 cm ³	0.29 €/cm ³	16	8	1		0.5
13	54.18 l	Not needed	13.5 €/l	350	10	10		4
14	33 g	1 g	0.06 €/g	1.9	2	0.4		0.5
15	312 g	32 g		1.9	2	0.4		1
16	37 cm ³	10 cm ³	0.29 €/cm ³	16	8	1		0.5
17	54.39 l	Not needed	13.5 €/l	350	10	10		4

Table 5. Sterilization cost model estimates.

Exp. ID	Sterilization Method	Sterilization Equipment Cost of a 60L Benchtop Autoclave (k€)	Cost of Sterilization Material 70% (€/L)	Amount of Alcohol Needed for a Batch (L)	Sterilization Equipment Annual Maintenance Cost (k€)	Length of Autoclave Process (h)	Hourly Sterilization Cost (€)
1						1.0	
2	Autoclave	15	-	-	1	0.5	1.04
3						1.0	
4						0.5	
5				0.5			
6	C3H8O	-	9	5.0	-	-	-
7				0.5			
8	Autoclave	15	-	-	1	1.0	1.04
9						0.5	
10				1.0			
11	C3H8O	-	9	5.0	-	-	-
12				0.5			
13	Autoclave	15	-	-	1	0.5	1.04
14	C3H8O	-	9	1.0	-	-	-
15				5.0			
16	C3H8O	-	9	1.0	-	-	-
17	Autoclave	15	-	-	1	0.5	1.04

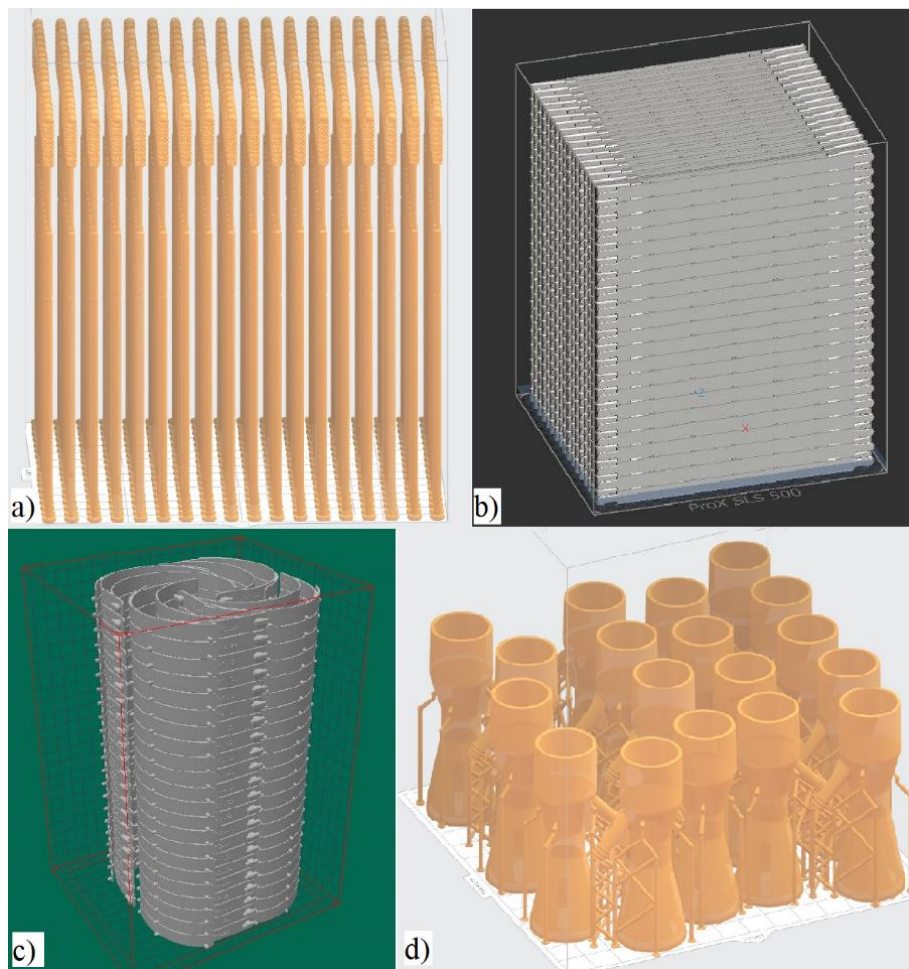


Figure 1. Packing solutions of parts in different build volumes: (a) nasal swab in Form 2; (b) face shield holder SLS optimized in ProX SLS 500; (c) face shield holder in ProX SLS 500; and (d) Venturi valve in Form 2.

3. Results

Products currently being manufactured using 3D printing in the COVID-19 pandemic are generally face masks, face shields, nasal swabs, and Venturi valves (Table 1). The estimated cost and productivity of different products with different 3D printing technologies, when extrapolated over the estimated amount of identical equipment in the market, are shown in Table 6. The results indicate the potential number of products that can be manufactured with one set of equipment, and with all the equipment available in the market. Table 7 lists the overall estimated costs. The most potential ones are those that have a high productivity with a single set of equipment and widespread availability of equipment in the market.

However, there are similar 3D printers from different manufacturers in the market that can be used to manufacture these products and devices using comparable materials. Thus, the total 3D printing potential in the world is in fact conservatively estimated to be at least 10–100 times larger, and therefore can have a huge impact on the lack of medical supply in the current situation. Furthermore, it should be noted that certain 3D printing technologies are better for manufacturing specific types of products than others. To this end, there is a need to deploy an optimal 3D printing technology for each application to maximize the production of required parts.

Table 6. The potential productivity of using 3D printing.

Exp. ID	Description	Equipment	Batch Size	Productivity Units/24h	Estimated No. of Equipment in the World	Total Potential Units/24h
1	Nasal swab	Formlabs Form 2	400	783	50k	39130k
2	Nasal swab	3DSystems ProX SLS 500	3254	2056	1k	2056k
3	Venturi valve	Formlabs Form 2	18	54	50k	2688k
4	Venturi valve	3DSystems ProX SLS 500	625	274	1k	274k
5	Venturi valve	Ultimaker 2	1	11	100k	1058k
6	Venturi valve	Ultimaker 2	47	10	100k	1040k
7	Venturi valve	uPrint SE Plus	24	17	5k	85k
8	Face mask + lid	Formlabs Form 2	1	6,1	50k	306k
9	Face mask + lid	3DSystems ProX SLS 500	120	79	1k	78k
10	Face mask + lid	Ultimaker 2	2	2,4	100k	244k
11	Face mask + lid	Ultimaker 2	18	2,2	100k	220k
12	Face mask + lid	uPrint SE Plus	2	3,9	5k	19k
13	Face shield holder	3DSystems ProX SLS 500	88	56	1k	55k
14	Face shield holder	Ultimaker 2	1	3,5	100k	350k
15	Face shield holder	Ultimaker 2	10	3,1	100k	314k
16	Face shield holder	uPrint SE Plus	1	6,9	5k	34k
17	Face shield holder (SLS optimized)	3DSystems ProX SLS 500	374	88	5k	437k

Table 7. The cost analysis of medical parts.

Exp. ID	3D Printer Including Maintenance (€)	Labor (€)	Raw Material (€)	Consumables per Batch (€)	Sterilization (€)	25% Overhead (€)	Total Cost of Producing a Single Item (€)
1	2.86	30	60.48	10	1.04	26.1	0.33
2	284.88	120	540.89	100	0.52	261.6	0.40
3	1.87	30	45.09	10	1.04	22	6.11
4	410.25	75	670.14	100	0.52	314	2.51
5	0.51	7.5	0.6	1	4.5	3.5	17.64
6	24.40	30	27.36	1	45	31.9	3.40
7	16.88	15	88.16	10	4.5	33.6	7.01
8	0.91	22.5	18.9	10	1.04	13.3	66.69
9	274.88	60	732.10	100	0.52	291.9	12.16
10	4.41	7.5	5.88	1	9	6.9	17.37
11	44.02	22.5	57.9	1	45	42.6	11.83
12	6.13	7.5	49.59	10	4.5	19.4	48.58
13	285	60	731.43	100	0.52	294.2	16.72
14	1.54	7.5	2.04	1	9	5.3	26.35
15	17.18	15	20.64	1	45	24.7	12.35
16	1.74	7.5	13.63	10	9.0	10.5	52.34
17	768.88	60	734.33	100	1.04	416.1	5.56

The total cost for each 3D printed batch is calculated by the summation of machine acquisition and maintenance costs, labor, raw materials, consumable items, sterilization, and a 25% overhead cost. To estimate the individual cost per part, the total cost of 3D printing the batch is divided by the size of the production batch. For instance, the cost of producing a batch of 400 nasal swabs using the Formlabs Form 2 machine is about 130.5 €, which translates to 0.33 € for a single nasal swab. Similarly, the cost of producing the same part on a ProX SLS 500, which is a larger industrial PBF machine, is 0.40 €, as shown in Table 7. The total cost of producing a single item with different cost components is shown in Figure 2. Two different batch sizes, used for the production of identical parts, in Ultimaker 2 confirm that a percentage increase in costs is significantly lower than the percentage increase in batch size. This is because certain pre- and post- processes, i.e., labor, sterilization, and overhead, which can be seen as dominating factors for small batches in Figure 2, are inevitable, and possess higher throughput capacity than just one or two parts.

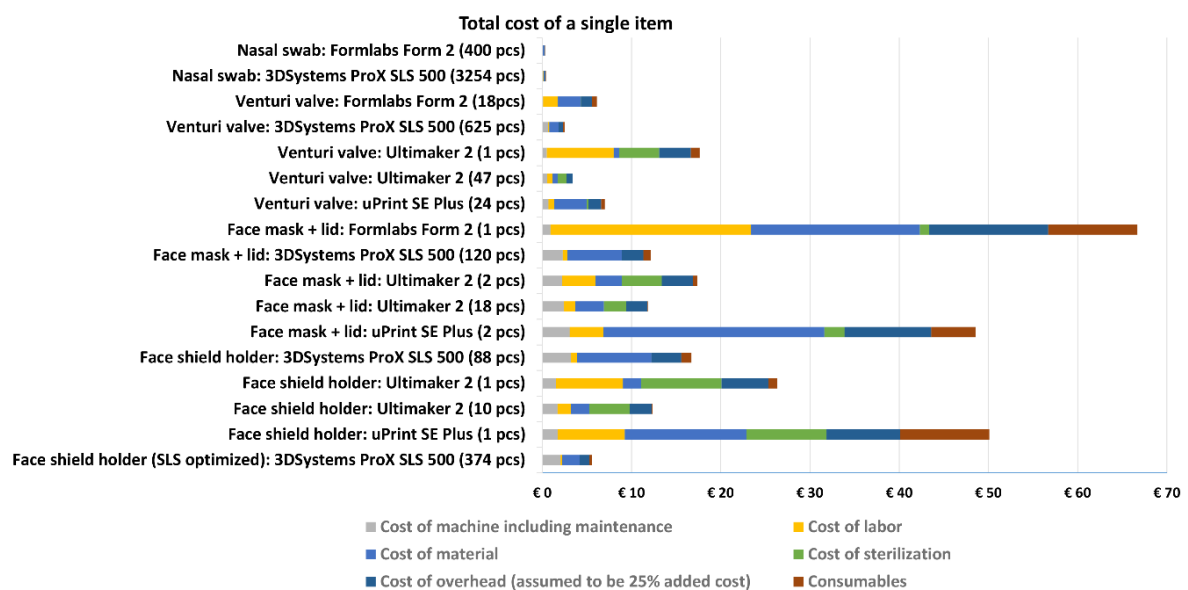


Figure 2. Total cost of producing a single item as a function of different 3D printers, batch sizes (shown in parentheses), and cost components.

4. Discussion

This study discusses the potential of using 3D printing (additive manufacturing) to manufacture products required during the COVID-19 pandemic in the year 2020. Examples of products include face shields, respirators, nasal swabs, and ventilator parts. Face shields and respirators pose an interesting challenge for manufacturers, to ensure that they are fabricated within the shortest time frame in which the efficiency of the design and shortest build time is paramount. However, they need an assembly phase, such as adding a transparent plastic shield or a filter. Parts for ventilators and nasal swabs pose a more technical challenge for manufacturers in light of intellectual patent laws. All the products are still required to have compliance with healthcare standards and regulations.

At the moment, some countries suffering from the pandemic have accelerated the approval process for using 3D printing to produce supplies for hospitals. Countries currently facing critical shortage of supplies have even had to bypass some stringent regulations and approval stages with the acceptance of run-of-the-mill solutions. One problematic factor is also the availability of 3D models for certain parts. Companies aim to protect their designs and their intellectual property (IP), but at the same time suffer from their limited manufacturing capacity. 3D printing may allow for an increase in the availability of manufacturing capacity to react quickly, but their unwillingness to share the designs will remain the greatest challenge. Nevertheless, open source community platforms, designers, makers, artists, and even some companies have started to embrace this movement to share their designs and have made

collaborative development possible. This chain reaction has sped up the solutions remarkably because people are able to incrementally innovate over each other, and there is a possibility to learn from what others have done. This has been one of the biggest reasons why 3D printing applications related to COVID-19 have been developed so rapidly.

Previous work has acknowledged that 3D printing can be used to support the spare parts market [27,28]. However, it must be noted that patent laws regarding such 3D printed spare parts will need to be further resolved in the future. The COVID-19 pandemic has increased the pressure on manufacturers to make their designs freely available, particularly in cases where spares may not be readily accessible due to disruption in production plants, logistics, and supply chains. Current spare parts are stored as physical inventory for which logistic networks or deliveries may not be functional. Lastly, if tooling is required to re-initiate production, this can contribute to increasing costs for companies and end-users. Another area of contention is that “repairing patent-protected products with digital spare parts could risk infringing upon the intellectual property rights (IPR) of patent holders” [27]. For example, to repair a protected device using a spare part, part of the invention may be reproduced, and thereby infringement can occur. Fortunately in most European jurisdictions, infringement only occurs if repair activities are undertaken for commercial purposes, and private use is therefore exempted [29]. The concept of “repair” is still interpreted differently in different EU member states, in terms of legitimate repair or when repair counts as infringing upon the rights of the patentee. There has been no agreement on the interpretation of “repair” in the EU, and further clarity is needed as to what extent producing, transforming, assembling, or constructing a product is considered to be “legitimate”.

To support the efforts towards the fight against COVID-19, the National Institutes of Health (NIH) [30] in the U.S. has made the computer-aided design (CAD) models of PPE products freely available on its website, and has also divided them into two categories. Non-critical products include air exchangers, filter adaptors, in-line filter housing, and pneumotachometers. Products that have safety implications include ventilator splitters, Venturi valves, and flow restriction devices that pose a much greater risk if used or produced incorrectly. This digital library was created to support the manufacturing of PPE and other medical devices in short supply due to the COVID-19 outbreak. The NIH, Food and Drug Administration (FDA), Veterans Affairs (VA), America Makes, and contributors acknowledged that they cannot ensure the quality, safety, and efficacy of these designs when manufactured without proper quality controls and processes. As a result, ASTM International [30] has enabled public access to relevant ASTM standards used in the production and testing of PPE such as for face masks, medical gowns, gloves, and hand sanitizers. Other efforts, such as the U.K. Government Office for Product Safety and Standards, have also published guidelines to assist manufacturing companies planning to convert their operations to produce PPE. These include ways to have products approved for sale or to be donated to the government to be used by healthcare workers. It also provides guidance on what manufacturers have to do to fulfil those obligations, and contacts to U.K. Notified Bodies that can assess PPE for COVID-19 [31]. However, it must be noted that at the time of writing, there are still no specific standards available when using 3D printing for the production of PPE to ensure total compliance with healthcare protocols.

In terms of the digital value chain when designing and producing parts for 3D printing, the ISO document, “ISO 17296-4:2016 Additive manufacturing - General principles - Overview of data processing” [32], suggests that data exchange methods could include the file type, data enclosed formatting of such data, and what this can be used for. Examples of suitable formats for data exchange include .STL, .STEP, and .AMF. Of these, the .STL file is still the most commonly used format, and this has been observed in the file formats available in the digital library for COVID-19 CAD files. One of the drawbacks is that .STL files do not specify units. Newer file formats have been made available, such as the .AMF file format that can contain metadata such as information of the CAD source, design and production specifications, supplier information, and production data. The .AMF file format is also able to support constellations that describe the build pack, stacking, nesting, or orientation of parts.

The .AMF file format is also XML-based, and users with a text editor are able to quickly open, view, and edit the metadata content. Other useful formats that could provide a more accurate and efficient manufacturing workflow include the .3MF file format.

3D printing in a bridge manufacturing mode has tremendously supported the fight against the COVID-19 pandemic [33]. Local or distributed manufacturing [34,35], supply chain modifications, and enhanced education can help us achieve a more stable supply chain, as well as mitigate a number of shortcomings [28,36,37]. The labor requirements for pre- and post-production steps of 3D printing, in addition to the throughput of the 3D printer, limited range of raw materials, and multi-material process constraints, call for further technological advancements to improve the competitiveness of 3D printing, and to deal with raw material shortages [38].

This study was limited to open source parts because they are accessible to everyone, and therefore have the biggest impact. The work used few exemplar parts to highlight the potential of 3D printing, however there is a wide range of similar open source parts made available in open access repositories. Future studies are recommended to focus on the technical verification of the parts. Cost and productivity models are estimations, and are simplified to provide valuable insights about the cost structure and productivity that 3D printing is capable of achieving in the COVID-19 pandemic.

5. Conclusions

To fully capitalize on the use of 3D printing during the COVID-19 pandemic for the production of parts in a state of emergency requires a technical know-how and understanding of technologies and materials that will conform to the quality and functional integrity of the intended products. In the ongoing viral outbreak, there is a very high demand for PPE, swabs, and spare parts, due to the breakdown of global supply chains. On the basis of the findings, our analysis provides statistical evidence that the most potential healthcare products that can be manufactured using 3D printing are those that have a high productivity with a single set of equipment and with widespread availability of equipment in the market. However, this new unregulated supply chain has also opened new questions concerning product certification and IP. There is a pressing need to develop 3D printing medical standards for current and future pandemics.

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