
Additive Production Management in COVID-19 Pandemic

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Abstract:

Purpose: The article aims to discuss the authors' own experiences and literature review on the topic of small communities of additive production in COVID-19 conditions and propose an improvement of emergency procedures in situations of global threat.

Design/Methodology/Approach: Its object is organizing and analyzing the experience gained during the production of healthcare products in 3D technology during the first wave of the COVID-19 pandemic.

Findings: Further objects include identifying problems, proposing solutions, signaling problems to be solved, improving the efficiency of managing the production and distribution of health protection products, and improving the energy efficiency of the production process.

Practical Implications: Structured conclusions and the resulting proposals for activities in the production and distribution of health protection products in situations of global life threat formulated further research goals.

Originality/Value: An in-depth analysis of the literature on the subject and the research results presented in the article indicate the need for further research on the concept of optimization of the production process in the context of the temporary market demand for specific products. The article presents a proposal for a model that allows the use of incremental techniques and cost optimization depending on the market demands.

Keywords: Additive manufacturing, management, online platforms, innovation, COVID-19, pandemic, 3D printing, recycling

JEL codes: D20, D40

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1. Introduction

The appearance of the pandemic in early 2020 was a significant surprise to humanity. This resulted in the collapse of the logistics industry at the global level and the freezing of countries' economies in many sectors. The most critical challenge was the lack of means of protecting life and health. The quick answer was the use of 3D printers (Imbrie-Moore *et al.*, 2020; Manero *et al.*, 2020; Tarfaoui *et al.*, 2020), which resulted in an increase in decentralized additive production (Choong *et al.*, 2020; Mehrpouya *et al.*, 2019; Mueller *et al.*, 2020). Many micro-communities or micro-consortia for medical additive manufacturing have emerged.

In response to the European Commission's call (European Commission 2020) for support in the fight against the COVID-19 pandemic, a range of initiatives and online platforms have been set up to bring together the 3D printing community in a technology-driven, cross-border, fast and effective pandemic control strategy. This has fueled the evolution of the global network of 3D printing community volunteers and experts, which pushes towards the optimum use of the regional 3D printing capabilities for a supra-regional response to primary product shortages and supply chain disruptions (Mueller *et al.*, 2020). The community's efforts to supply hospitals were focused on addressing different shortages and bringing together enough micro-production sites to have an aggregate support for the real-time need (Manero *et al.*, 2020).

For instance, in Europe, in the initial days of the outbreak in Italy, Isinnova and FabLab engaged themselves in printing ventilator spare parts (valves) for a hospital in Brescia. When they succeeded, more 3D printing companies followed suit and started supporting Italian hospitals in the same manner (Choong *et al.*, 2020).

Lombardy-based WASP (Industry Europe 2020) has taken up printing of custom face masks for individual wearers which reduce skin irritation related to long-term use. In Spain, the second most pandemic-affected country after Italy, a group of 800 people representing the 3D printing industry (engineers, designers, and individual enthusiasts) set up a co-working group. 3DCovid19.tech (3Dcovid19 2020) is a not-for-profit platform which accepts orders from hospitals and publishes new ideas, files and printing instructions for protective supplies and accessories. The platform enabled taking orders from 11 hospital centers in Barcelona, Madrid, Castilla-La Mancha, and Andalusia in less than 24 hours.

3D printing has played a key role in countering the pandemic in Poland as well. For instance, there was the grassroots initiative #DrukarzedlaSzpitali (Drukarze, Dla, and Szpitali, 2020), in which 3D printers, designers, engineers and volunteers worked together to develop replacement goggles, visors or ventilator T-tubes. Many universities and schools throughout Poland have become engaged in manufacturing of this kind of medical equipment (Krolikowski *et al.*, 2020). Engineers and designers from Urbicum in Krakow (Urbicum, 2020) have joined their forces in the VentilAid

project. They are designing an open-source ventilator (Frazer, Shard, and Herdman 2020) that can be reproduced using a 3D printer and a set of basic and easily available parts. The Łukasiewicz Research Network and the Institute of Biocybernetics and Biomedical Engineering are developing a device that will enable sharing one ventilator between two patients.

Many platforms have been created globally to coordinate support in the fight against the pandemic. One of the largest 3D print/AM application databases in response to COVID-19 was launched on the 3D printing website of the US National Institutes of Health, which cooperate in this respect with the AmericaMakes initiative and the Department of Veterans Affairs. Royal DSM, a global science-based company operating in the nutrition, health, and sustainable living sectors, launched UNITE4COVID, a digital, open, collaborative marketplace designed to provide solutions for healthcare professionals, as well as a forum and collaboration hub for inventors, manufacturers and certification labs in the fight against the coronavirus. The European Cluster Collaboration Platform (ECCP) set up the COVID-19 response forum, and the Enterprise Europe Network launched the European cooperation platform for care & industry together against CORONA (Care and Industry together against CORONA 2020).

It is impossible to mention all the initiatives here. Many businesses and individuals engaged in 3D printing globally, including such giants as Stratasys, Hewlett-Packard (manufacturer of 3D printers), Materialise (Belgian provider of 3D printing services), or PrusaPrinters (Josef Průša's company in the Czech Republic), have published free 3D printing models of accessories for the fight against the pandemic on their websites. Thingivers and myminifactory are the most famous sites, and so is CAR3D, the first European 3D printing project to create COVID-19 protection equipment. Siemens, too, has opened its Additive Manufacturing Network (AMN) platform to support efficient design and 3D printing of medical components needed by hospital staff to counter the COVID-19 pandemic.

The main goal of this paper is to discuss the experiences of the authors and literature review on the topic of small communities of additive production in COVID-19 conditions and present proposals to improve the procedures in situations of global threat. Most common difficulties were identified. The focus was on:

- work organization,
- human safety in terms of the possibility of infection and the impact of volatile organic compounds released during additive production,
- obtaining filaments,
- rapid prototyping before putting into service (testing mechanical properties and toxicity),
- the energy efficiency of the production process,
- remote communication,

- distribution of health protection products,
- method of financing.

Opportunities to improve activities in the protection of human health were indicated.

2. Materials and Methods

The 3D Printing Center of the Koszalin University of Technology responded to the needs of local public institutions at the beginning of global lockdown. The lack of a continuous supply chain from contractors had a significant impact and could disturb the production after running out of stock. In fear of not meeting the demand, it was necessary to use an extraordinary approach and use of resources. As a result, it was decided to process old FDM 3D prints and waste for filament preparation on site.

3devo Shr3dIT and Composer450 were used. Old PET-G prints and PET bottle scrap were color sorted first and minced with Shr3dIT into flakes form (Figure 1a). Next, the material was dried for 24 hours at 60 ° C and doped with pigments before extrusion. The experimentally determined operating parameters of the 3devo Composer450 device were, rotational speed of feeding and mixing screw 4 rpm, temperatures in 4 heating zones 200, 220, 230 and 210 ° C, cooling fans 50% and winding speed was set to automatic. The selected parameters allowed to obtain a filament diameter of 1.75 within acceptable tolerance of ± 0.1 mm.

Figure 1. Preparing filament printers (a) Shr3dIT minced prints in Composer 450 feeding hopper; (b) DevoVision app screen from Composer450 with measured filament diameters



(a)



(b)

Source: Own study.

To ensure safe use, headbands made from different blends of both materials (PET and PET-G) were then tested on a universal testing machine. Due to the amorphous nature of the material and concerns about increased crystallization because of PET addition,

leading to increased brittleness of the product (Demirel, Yaraş, and Elçiçek 2011; Young and Lovell 2011), the tests were focused on checking its tensile strength. The initial design of the helmet headbands was based on Prusa's RC2 project, which was made available under an open-source license. However, during the research, many modifications were made to optimize time, material consumption and to meet feedback suggestions from ordering institutions (Figure 2).

Figure 2. Protective helmets made with the use of 3D printers (a) Employee of the Koszalin University of Technology in the prototype of the helmet; (b) Helmets prepared to be handed over to the test group



Source: Own study.

Prototyping: Most of the helmet bands were made of filaments made in-house from PET bottles. Before the production of the masks started, prototypes were made, and the functional properties were tested. Figure 3 shows the tested item.

Figure 3. The printed part of the helmet prepared for tests



Source: Own study.

At first, the simulation research was done. The item presented in Figure 2 was simulated to be under static load. Deformation and stress were evaluated. A linear elastic model of the material was assumed. Here, the dependent variable is the value of displacements u at individual points of the tested system and the value of stress s

described by the equation for bodies with linear-elastic properties in the form (Brower, 2005):

$$-\nabla s = FV$$

where s the stress tensor, FV the vector of external excitations. In terms of relatively small deformation values, the relation of stress to deformation, represented by strain ε , is described by the Duhamel-Hook law, formulated in the form of the following relation:

$$s = s_0 + C : (\varepsilon - \varepsilon_0)$$

where C is the stiffness tensor for the beam, the tensors s_0 and ε_0 are the stresses and initial deformations in the material, respectively. When the stress and displacement tensors are symmetrical, the stresses can be represented as the product of the stiffness and strain matrices. When linearized movements are assumed, relationships between deformations and displacements describe Cauchy relationships:

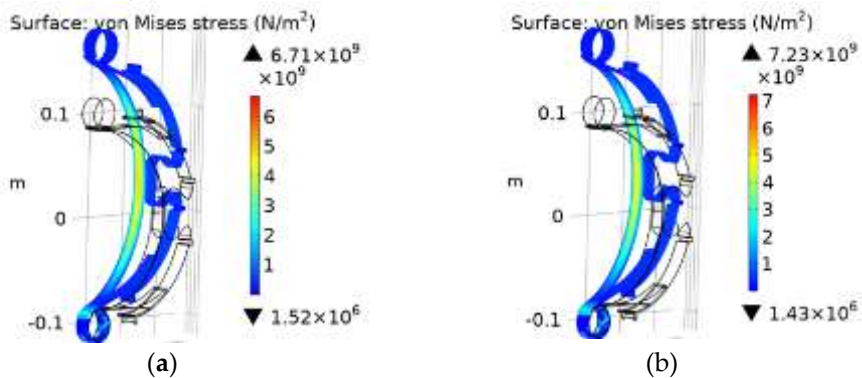
$$\varepsilon = 1/2 [(\nabla u)T + \nabla u]$$

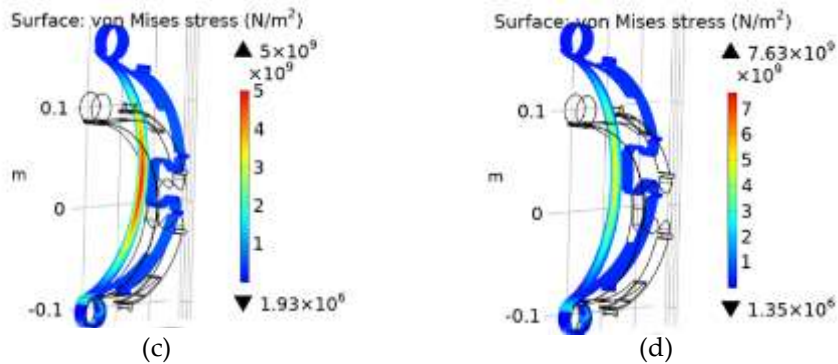
where u is the displacement vector to be identified with the stress tensor s by simulation tests.

3. Results

It was possible to examine different compositions of materials used. It was mentioned above that PET and PET-G mixture is examined. Figure 4 shows the results for four PET and PET-G material configurations under static force.

Figure 4. Displacements and von Mises stress caused by a vertical force of 150N in the item made from: (a) 50% PET and 50% PET-G, (b) 70% PET and 30% PET-G, (c) 100% PET-G, (d) 100% PET.





Source: Own study.

The 150N load was applied vertically, as in Figure 5.

Figure 5. Stand for strength tests of printed PET helmet bands



Source: Own study.

The tensile strength for material PET with growing percentage addition of PET-G decrease from 60,2 MPa, for pure PET, to 46,4 MPa, for pure PET-G. As the simulations (Figure 4) showing, the maximal stress exceeded about ten times the tensile strength, in each case for the vertical force 150N. The likely breaking points are clearly seen, where maximal von Mises stress are present. Practically, the strength properties were tested, giving priority to the usable aspects of durability and user safety.

Only the strength properties were tested, giving priority to the functional aspects of durability and user safety. The endurance test stand is shown in Figure 5, and the obtained results are presented in Table 1.

Due to the lack of time, the dynamic properties were omitted (Knitter *et al.*, 2021; Krolikowski, Knitter, and Blazejewski 2019; Krolikowski, Knitter, and Stachnik 2019). The safety-relevant toxicity of volatile organic compounds formed during the

creation of the band was also disregarded. For aesthetic reasons, pigments were added to the production of the filament, which can also be toxic (Pajak, Rybinski, Dobrzynska, Janowska, and Zaczek, 2015).

Table 1. Tensile strength tests for 3D printed head bands

F_{max} [N]	$\Delta L(F_{max})$ [mm]	F_d [N]	$\Delta L(F_d)$ [mm]
288	115,7	280	115,8
267	113,3	265	113,3
273	111,9	273	111,9
374	78,5	331	78,5

Note: F_{max} – maximum force, $\Delta L(F_{max})$ – increase in elongation for maximum force, F_d – destructive force, $\Delta L(F_d)$ – increase in elongation for the destructive force.

Source: Own study.

For the safety of staff and volunteers, the workroom was well ventilated, and the filaments were produced in a separate room, with the use of additional personal respiratory protection equipment.

Production management: After obtaining positive results of endurance tests, the production of the helmets was started. The production of the helmets was carried out on FDM printers; a total of 25 Creality Ender3 devices worked continuously. Initially, parts of helmets were printed individually, which allowed preparing about four helmets on each printer during a working day. One hundred pieces a day were printed in total. The printing of a single helmet, lasting about 2 hours, was extended by an additional 10-15 minutes by cooling the build plate, removing the printout and preparing the printer for the next print.

Considering that the procedure was repeated 3-4 times on each printer daily, it was necessary to optimize the workload and electric power consumption. During the warm-up phase, the printer consumes about 280 W energy per hour, while during operation, this value is just 120 W per 1 hour. The printing of one helmet consumed approximately 0,275 kWh, 35 W for 10 minutes of warm-up and 240 for 2 hours of printing. After process optimization, the elements were printed in stacks of 10 items. This solution allowed to increase the daily production up to 250 pieces and reduce the average energy costs by reducing the number of heating phases of the device by 90%.

The 22-hour print cycle also allowed for better organization of the entire process. The production of elements could be easily carried out by one person. The printouts finished around 7 am, so when the employee started work at 7:30, the printers working platforms were cooled down and allowed for efficient removal of printouts in less than 30 minutes. Between 8 am and 9 am, it was possible to carry out the review and maintenance of equipment, supplement filament, and start the next print, ending the next day at 7 am. The employee could then begin separating and cleaning plastic elements, which were then assembled into the final product by volunteers.

Table 2. Tensile strength tests for 3D printed head bands

Process optimization stage	Daily production [pc]	Energy consumption per unit [Wh]	Per unit warm-up energy consumption [Wh]
before	75 ÷ 100	275	35
after	250	243,5	3,5
change	+ 150 ÷ 233%	- 11,45 %	- 90%

Source: Own study.

Distribution: All manufactured helmets were issued free of charge. They were given to public institutions, primarily for the health service. In the beginning, the helmets were delivered by university employees. Each institution interested in receiving assistance in this form could call the telephone number provided in the media and report its demand. The only requirement of the university was the necessity to collect the helmets by the ordering institutions from the neighborhood.

Financing: The external financing of materials to produce the heads by sponsors allowed the production of 14.5 thousand helmets. In addition to the large group of individuals who donated and helped, it is worth mentioning public institutions and companies: the City of Koszalin, the Rural Commune of Kołobrzeg, Radio Koszalin, Waterworks of West Pomerania, ABWood, 4System, Global3D.

4. Discussion

The community's efforts to supply hospitals focused on addressing various shortages and bringing together many micro-production sites to aggregate support for the growing real-time need (Manero et al. 2020). This was possible owing to community involvement and online cooperation platforms for 3D printing (Rayna, Striukova, and Darlington, 2015). The initial experience additionally showed the challenges faced by organizations engaged in 3D printing during the pan-demic.

Firstly, the interrupted supply chains, lockdowns and closed borders led to short ages in supplies of products, materials, and production inputs, including 3D printing filaments. In response, commonly available materials were used, such as PET bottles in own experiences presented in this paper.

It was also a challenge during the pandemic to filter big data sets to identify genuine real-time needs, mainly to match the needs of medical services to community partners and volunteers who had the capabilities to manufacture PPE and the necessary equipment for hospitals and healthcare services. This was done through spontaneous collaborative platforms that supported matching the demand side with 'printers' and volunteers offering their assistance.

Another challenge was to find, and catalogue proven designs and to adapt them to the manufacturing capabilities of individual ‘printers. Most PPE designs were published by individuals on various online 3D printing community websites and had not undergone any official functional testing, approval or certification processes usually required for PPE, and even more for medical devices (Mueller *et al.*, 2020).

Furthermore, volunteers who manufactured equipment for healthcare professionals faced logistics issues. They were dispersed, and therefore it was a considerable challenge to supply the required materials to printers, collect their products, and deliver them to hospitals. There was a need for reliability and mitigation of cumulative risk. In Poland, the military, voluntary fire-fighting services and even Publish Postal Operator often came to the rescue in the case of logistics problems. Moreover, several companies sponsored bicycle rentals for volunteers or purchased bicycles for their staff to help them deliver the equipment to the point of use without taking any additional risks.

A chance to overcome these difficulties may be creating an internet cooperation platform that would connect all interested parties in one place. Its goal would be to match the demand side (healthcare services, hospitals, paramedics, social workers) with community partners who have the capabilities to manufacture PPE and the necessary equipment – enabling them to use tested and proven solutions (open source and crowdsource 3D printing designs/models), and with volunteers who will distribute the required materials (such as PET bottles) and deliver 3D printing products to the point of destination. In this respect, public interest organizations and regional and local authorities (Farrugia and Plutowski, 2020) play a significant role. This is particularly important due to the sense of security and trust in remote collaboration platforms (Wagner and Strulak-Wójcikiewicz 2020; Wagner, Strulak-Wójcikiewicz, and Landowska 2019).

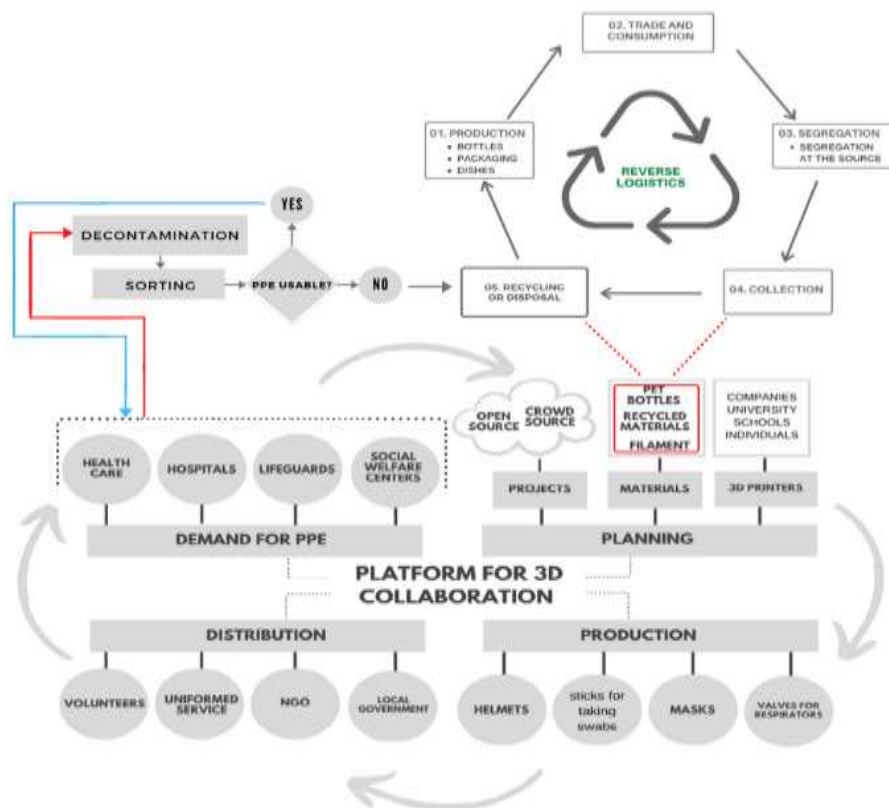
The SARS-CoV-2 pandemic has also contributed to adverse environmental impacts due to the use of large quantities of disposable masks, protective clothing, plastic visors and PPE components (Patricio Silva *et al.*, 2021). Therefore, the possibility of safe recycling (with prior de-contamination) and reuse of these materials should be contemplated (Sabahat, Naeem, and Meo 2020), as well as the development of proper infectious waste management (Patricio Silva *et al.*, 2021).

In view of the availability of PET as an input for 3D printing, the collaborative platform should include the concept of reverse logistics and cooperation with local waste collection, recycling, processing, and disposal companies. However, it is essential to emphasize that PETs are collected with other plastic waste during selective collection from individuals. This necessitates additional processes to separate this kind of specific waste (Patricio Silva *et al.*, 2021). Because of the ‘littering’ of the environment with pandemic waste, it is necessary to include in the collaborative platform the operators engaged in the reuse (Mackenzie 2020; Peltier *et al.*, 2020; Saini *et al.*, 2020) and recycling of single-use PPE. This process encompasses

decontamination and disinfection, as it often involves PPE and infectious waste, which require appropriate decontamination and disinfection methods and procedures (Rowan and Laffey 2020). Especially that studies in this area are ongoing, they are being tested and often put into practice (Ilyas, Srivastava, and Kim, 2020).

In response to the above-mentioned problems, the authors of the paper put forward a concept of a cooperation model for 3D printing in COVID-19 conditions presented in Fig. 6 which considers some of the problems formulated above (Strulak-Wójcikiewicz and Bohdan, 2021).

Figure 6. The concept of the platform cooperation model for 3D printing in COVID-19 condition [34]



Source: Own study.

The concept presented herein brings all interested parties together in a collaborative platform. Its purpose is to match the demand side (healthcare services, hospitals, paramedics, social workers) to community partners who have the capabilities to manufacture PPE and the necessary equipment – enabling them to use tested and proven solutions (open source and crowd source 3D printing designs/models) and to volunteers who will distribute the required materials (such as PET bottles) and deliver 3D printing products to the point of destination.

In additive manufacturing, volatile organic compounds are released that have a negative impact on human health. Adequate ventilation is required during simultaneous printing on multiple printers (Królikowski *et al.*, 2019). Due to a large amount of waste heat, its recovery should also be considered, which will significantly improve the energy efficiency of additive production. Heat recovery can be compared to heat recuperation in paint shops (Adamkiewicz and Nikończuk, 2019), spray booths, where the air is exchanged (Nikończuk, 2018; Nikończuk and Rosochacki, 2020) or the use of heat pumps that enable high efficiency (Nikończuk and Tuchowski, 2021).

Therefore, it is reasonable to include a module in the platform containing information on places with adequate ventilation and heat recovery allowing collective placement of printers. However, it is essential to consider the need for sufficient distance and other safety measures to prevent transmission of infection.

5. Conclusions

During the first wave of the pandemic, the Koszalin University of Technology, and the Secondary School of Kolobrzeg consortium produced over 20,000 protective helmets, including 15,000 at the Koszalin University of Technology. While analyzing the production, several more critical problems were identified that were partially resolved on an ongoing basis. This concerned the organization of work where the production efficiency was optimized up to 250 helmets per day while reducing electric power consumption. Adequate ventilation is also provided due to the release of volatile organic compounds. The logistic problem of delivering the helmets was solved by having interested institutions collect the helmets themselves. PET bottles were individually obtained using courtesy transport.

However, it is reasonable to solve the logistic problem using an appropriate transport model at least within the city Chamier Gliszczyński, 2011a; 2011b). The financing for the purchase of necessary printing elements was also partially obtained, and the filament was produced from recycled PET bottles.

Based on the above experiences, it was concluded that the main part of the development of means of responding to crisis situations should be an internet platform containing an information bank and modules for communication and optimization of the issues described above. The main feature of such a platform should be its scalability and ease of extension with additional modules.

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