Community-Driven PPE Production using Additive Manufacturing During the COVID-19 Pandemic: Survey and Lessons Learned

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Abstract

This study presents a detailed analysis of the production efforts for personal protective equipment in makerspaces and informal production spaces (i.e., community-driven efforts) in response to the COVID-19 pandemic in the United States. The focus of this study is on additive manufacturing (also known as 3D printing), which was the dominant manufacturing method employed in these production efforts. Production details from a variety of informal production efforts were systematically analyzed to quantify the scale and efficiency of different efforts. Data for this analysis was primarily drawn from detailed survey data from 74 individuals who participated in these different production efforts, as well as from a systematic review of 145 publicly available news stories. This rich dataset enables a comprehensive summary of the community-driven production efforts, with detailed and quantitative comparisons of different efforts. In this study, factors that influenced production efficiency and success were investigated, including choice of PPE designs, production logistics, and additive manufacturing processes employed by makerspaces and universities. From this investigation, several themes emerged including challenges associated with matching production rates to demand, production methods with vastly different production rates, inefficient production due to slow build times and high scrap rates, and difficulty obtaining necessary feedstocks. Despite these challenges, nearly every maker involved in these production efforts categorized their response as successful. Lessons learned and themes derived from this systematic study of these results are compiled and presented to help inform better practices for future community-driven use of additive manufacturing, especially in response to emergencies.

Keywords: COVID-19, distributed manufacturing, makerspaces, 3D printing, social production systems, community-driven production

1. Introduction

The rapid spread of the 2019 novel coronavirus disease (COVID-19) around the world placed a strain on health care systems and led to a surge in demand for adequate Personal

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Protective Equipment (PPE) for healthcare workers treating COVID-19 patients. Meanwhile, PPE supply chains were disrupted due to travel bans, stay-at-home-orders, and a rapid increase in the number of cases leading to widespread shortages of PPE [1]. Many organizations that do not typically produce PPE, such as universities and community makerspaces, mobilized production in response to this nationwide shortage using informal and distributed production spaces [2], efforts which we refer to as community-driven production. The participation of makerspaces and universities was unprecedented and undoubtedly served a role in rapidly responding to the shortage of medical PPE supplies utilizing Additive Manufacturing (AM). This emergency highlights how the flexibility, ease of use, and ubiquity of AM technologies (often called 3D printing) in universities and makerspaces around the world make it a plausible solution for crisis-driven flexible and distributed manufacturing over short time scales. However, most of these community efforts were undertaken on an ad-hoc basis and, understandably, had lower production rates than typical PPE manufacturing technologies. To prepare for future supply chain disruptions where flexible and distributed manufacturing processes such as AM can be better leveraged, we need to understand and reflect on the efforts made by the makerspaces and universities.

To understand the role of makers in producing PPE, it is necessary to understand the broader context of efforts to meet medical supply shortages and to survey related academic literature analyzing different responses to the shortages. In the US, for example, according to recommendations published by the US Centers for Disease Control and Prevention (CDC), healthcare workers treating COVID-19 patients should be protected using regularly changed PPE including face shields/goggles, N95 or higher-grade respirators, gloves, and gowns [3]. By March 2020, PPE and ventilators were in high demand worldwide, and there was a pressing need for extensive and rapid domestic production to ensure adequate supply. Large companies like Ford Motor Company and Boeing came forward to produce emergency healthcare equipment, but these production efforts needed substantial lead times and could not meet immediate demand, which was surging [4, 5]. In response to the shortage of key medical equipment, the CDC issued and revised guidelines, such as procedures to curb usage of filtering facepiece respirators by non-healthcare workers [6]. The Food and Drug Administration (FDA) began several initiatives including: 1) issuing Emergency Use Authorizations, which allowed certain medical products (e.g., respirators and face shields) to be produced and used on an emergency basis [7]; 2) collaborating with manufacturers to increase the availability and productivity of the medical supplies for caregivers and COVID-19 patients [8]; and 3) supporting small businesses, makerspaces, academic institutions, and individuals in their exploration of using AM to manufacture medical supplies [9].

There were numerous coalitions among government organizations, universities and medical facilities, different companies, makerspaces, and individuals to strengthen the AM network, as summarized by Manero et al. [2]. The FDA partnered with the National Institutes of Health (NIH), Department of Veterans Affairs, and America Makes to collect, test, and validate different designs of 3D-printable medical equipment, and to provide guidance to the interested makers [2]. With the guidelines and approvals from the regulatory bodies, many individuals, some affiliated with makerspaces and academic institutions, came forward to address the demand. Their efforts spanned from designing these critical products to production and distribution [10]. Many of these efforts focused on producing face shields because of its simple design and relaxed requirements from

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FDA [11]. Face shields were recommended for eye protection by CDC, [3], and were used to minimize the risk of extended use of N95 respirator during shortages [12]. In response to PPE shortages, many individuals in the maker communities and universities started to produce face shields using AM equipment [11].

Efforts at universities and makerspaces operated independently, utilized different AM technologies and equipment, and involved individuals with varying backgrounds and expertise. Data regarding their approaches (e.g., production methods, costs, time, quality issues, difficulties faced, and end-user feedback) will help us build a robust emergency response system where informal community-driven production efforts are more efficient and effective. This study seeks to investigate, quantify, and summarize relevant production variables related to the responses of makerspaces and universities where AM was utilized to produce PPE in the United States. Specifically, our goal is to systematically investigate the success of these efforts in relation to influential factors such as product designs, material type, AM process type, available resources, and production logistics to measure efficiency of community-driven distributed production and to identify best practices and areas for future research. Data is gathered from two sources: a review of news articles describing the efforts and a detailed survey completed by individuals who contributed to the efforts. It is worth noting that the review of news articles was needed in this work because it is the dominant source of information about community-driven AM efforts in response to the COVID-19 pandemic. In the next section, we review existing literature to identify related work and highlight research gaps that our study seeks to fill. The methods and study results follow in Sections 3 and 4, respectively. Following an analysis of these results, we present recommendations to improve the efficiency of future efforts in Section 5. Finally, Section 6 draws the paper to its conclusion.

2. Literature review

Given the recent onset of the COVID-19 pandemic and resulting efforts to produce PPE, scientific literature is quickly evolving, with new analyses and summaries being published almost every day. Our literature search included publications that appeared online before mid-February 2021. In this section, we summarize common themes of the literature that we have identified related to AM in response to the COVID-19 pandemic. In Table 1, we categorize different publications by the common topics that are covered thus far in the emerging literature on the role of AM in response to the COVID-19 pandemic. In what follows, we briefly review this literature and highlight the key findings in the respective topics categorized in Table 1.

2.1. Advantages of AM in response to the COVID-19 pandemic

AM technologies have many characteristics that proved useful in producing emergency medical supplies in response to the COVID-19 pandemic. Because some AM technologies require less operator training and design skills than traditional manufacturing processes, production can be scaled up on an emergency basis with low-skilled manpower [13, 15] and minimal operator intervention [14]. AM also offers fast prototyping [13, 16, 17] by eliminating the need for special molds, tools, and/or fixtures [5]. From a logistical viewpoint, the production of emergency equipment close to the end-users reduces warehousing and transportation requirements which can shorten response time as well as the product

Table 1: Summary of common topics discussed in existing literature focusing on using AM to respond to shortages of PPE due to the COVID-19 pandemic

Topic		Literature
AM advantages	Reduced workforce needs	Nazir et al.[13], Haq et al.[14], Longhitano et al.[15]
	Fast prototyping & production	Arora et al.[5], Nazir et al. [13], Choong et al.[16], Patel & Gohil[17]
	Redesign for efficient production	Nazir et al.[13], Haq et al.[14], Mueller et al.[18]
	Can produce a wide range of parts	Kunovjanek et al.[19], Choong et al.[16], Patel & Gohil[17]
AM limitations	Limited functionality	Frazer et al.[20], Bezek et al.[21]
	Sterilization & reuse are difficult	Longhitano et al.[15], Mueller et al.[18], Zuniga & Cortes [22], Tarfaoui et al.[23]
	Print & material quality variation	Mueller et al.[18], Longhitano et al.[15], Clifton et al.[24], Kunovjanek et al.[19]
Summary of AM efforts	Several efforts	Manero et al.[2], Tino et al.[25], Nazir et al.[13], Oladapo et al.[26], Belhouideg et al.[27], Advincula et al.[10], Tareq et al.[28], Novak et al.[11], Tarfaoui et al.[29], Frazer et al.[20], Kunovjanek et al.[19], Longhitano et al.[15]
	Design/production of a specific part	Mueller et al.[18], Amin et al.[30], Celik et al.[31]
Comparison of designs	Build time & complexity	Wierzbicki et al.[32], Novak et al.[33], Rendeki et al.[34], Wesemann et al.[35], Salmi et al.[36]
	Functionality	Wesemann et al.[35], Bezek et al.[21]
Challenges & recommendations	Production challenges	Kunovjanek et al.[19], Advincula et al.[10], Mueller et al.[18], Manero et al.[2], Singh et al.[37], Tareq et al.[28]
	Recommendations	Manero et al.[2], Sinha et al.[38], Tino et al.[25], Vordos et al.[39], Choong et al.[16]

cost [5]. AM enables part consolidation to decrease assembly operations and time, and part geometry can be readily changed to reduce cost, weight, and material waste of the product [13, 14, 18]. Moreover, AM machines offer flexibility because they can easily alternate between producing a wide range of complex products [16, 17]. A systematic review of 289 additively manufactured parts manufactured in response to COVID-19 demonstrated the wide range of uses of AM in times of emergency [19]. These advantages, coupled with the widespread availability of AM technologies, enabled the rapid production and distribution of emergency medical supplies in 2020. Existing literature has focused on high-level advantages and general technical aspects of using AM in response to the COVID-19 induced PPE supply chain disruption, but there is still a need to studying the specifics of makers' efforts.

2.2. Limitations/risks of AM

Although AM had advantages in addressing the supply and demand gap of PPE during COVID-19, the technology has limitations in terms of designs, materials, print quality, and productivity. Although printing medical devices and PPE may seem simple to hobbyists, the manufacture of such products to meet design requirements can be complex [20]. Many medical devices such as ventilator splitters are not suitable to be produced using fused filament fabrication due to weak bonding between layers and breakdown under moisture [20]. Designs such as the Copper3D NanoHack mask lacked acceptable functionality initially [25]. A recent evaluation of the filtration efficiency of additively manufactured masks found the efficiency to be generally quite low, with some designs performing worse than simple cloth masks [21]. The increased demand for PPE resulted in an increase in the importance of reusability, but many medical devices made using AM were prone to contamination and difficult to sterilize, limiting their reuse [15, 29]. This limitation prompted researchers to develop AM polymers with antimicrobial properties [22]. From existing literature, it is unclear to what extent functionality of parts was evaluated in community-driven responses, or how functionality considerations impacted their development process.

Another issue is that some of the materials and processes used were not suitable to ensure proper print and product quality [15, 18, 19]. Because multiple process parameters and material variation influence the geometric quality and mechanical properties of additively manufactured products, it is necessary for the makers to have adequate knowledge of AM processes to achieve quality and functionality requirements [15, 18]. As AM efforts were undertaken by people with different levels of expertise, quality and functionality variations might have occurred even for the same design. Moreover, AM efforts for PPE production had limitations because the available designs lacked standard validation and testing, infection prevention conformity, and proper print specifications to ensure reproducibility [24]. To create guidelines for future responses, we need to better understand to what extent these limitations impacted community efforts responding to the COVID-19 pandemic in 2020.

2.3. Summaries of AM efforts and comparison of AM designs

The most common goal of relevant literature published to date was to summarize applications and development of various medical equipment produced using AM by different companies, academic institutions, and healthcare organizations. We identified

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twelve relevant papers that summarized several different efforts to produce parts using AM [2, 10, 11, 13, 15, 19, 20, 25–29]. These summaries of different responses focus on offering high-level summaries and typically include both community-driven and industry-driven responses. Detailed, quantitative analysis of community-driven responses is still needed.

Another common focus in the literature is to present a case study that describes a specific part or a single production effort. For example, Mueller et al. (2020) described quality variation in parts, variation of material quality from different suppliers, and high amount of waste during the production of face shield headbands at Karlsruhe Institute of Technology [18]. Tarfaoui et al. [29], Amin et al. [30], and Celik et al. [31] also presented case studies focused on the design and production of a specific part. Researchers have also compared different digital design files of PPE that were created and freely shared online based on metrics such as their printing time, filament usage, estimated cost, functionality, disinfection effects, and part geometry [21, 32–36]. Findings of these studies indicate that certain designs were more efficient to print in terms of printing time and material usage and had varying levels of functionality. Existing literature does not provide specific details about how different designs were used in community-driven responses or describe implications of design choices on the production rate and overall impact of the production effort.

2.4. Production challenges/recommendations

Our survey of case study literature identified several common challenges associated with AM production of emergency medical equipment. Common challenges included supply shortage of raw materials, design challenges to ensure proper functionality, finding optimal printing parameters, and safety concerns of operators and transportation partners [2, 10, 18, 19, 28, 37]. Analysis of different efforts also identified recommendations for future pandemics. In 2020, government initiatives and communication structures were helpful for COVID-19 response efforts coordination and should be continued in the future. Numerous coalitions among different organizations (e.g., government, universities, companies, makerspaces) strengthened the AM network by encouraging, guiding, and coordinating the efforts [2, 16]. Social media was helpful in the development and coordination of PPE using AM [39]. General recommendations for future emergency use of AM have been included in many studies, with emphasis on topics such as safety guidelines and regulatory considerations [2, 25, 38]. In this study, we seek to understand challenges specific to community-driven responses and derive recommendations based on our analysis.

2.5. Current research gaps

The focus of existing literature is either very specific (e.g., case studies focused on descriptions of the design and production of a specific part) or very broad (e.g., high-level surveys of several efforts from industry and academia, followed by general commentary on challenges regarding quality or safety). Meanwhile, current literature did not focus on the specifics of community-driven efforts. Community-driven efforts at universities and makerspaces were decentralized and spearheaded by many individuals with different backgrounds, expertise, and equipment. Based on the current literature, it is unclear what types of designs, materials, and production practices were commonly utilized in

community-driven production efforts during the COVID-19 pandemic. While individual efforts have been summarized in case studies and various recommendations have been published, there is a lack of systemic survey and analysis of disparate community-driven production efforts. Additionally, although details were published for a few efforts, specific data is generally lacking. The variation in production rate, types of AM technology used, and success of these efforts has not been comprehensively analyzed. To address these gaps and better prepare for the next manufacturing disruption, we focus in this study on collecting and analyzing data from individuals involved in these efforts. From these analyses, we derive lessons learned to understand how informal, community-driven AM efforts can be better used for flexible and distributed manufacturing in times of crisis.

3. Methods

To investigate the community-driven manufacturing response to the COVID-19 pandemic incurred shortages in medical supplies, we identified makerspaces and other organizations that were active during the shortage period. We identified organizations using news articles and websites describing their response to the COVID-19 pandemic. The identification of these organizations served two purposes. Articles about the efforts undertaken by these organizations were used to conduct a high-level observational analysis. Also, individuals at each organization who were identified in the news articles were contacted to ask them to complete a survey to collect detailed quantitative data about their effort. A list of organizations was created using systematic Google searches with a specific focus on effort involving AM. Our search strings were as follows:

(1) ("face shield" OR 'face mask") ("3D printed" OR "3D printing") COVID University
(2) ("face shield" OR "face mask") ("3D printed" OR "3D printing") COVID makerspace
(3) ("3D printed" OR "3D printing") COVID makerspace

Search strings were developed using facet analysis to disassemble our topic into its essential parts such as population of interest (i.e., university and makerspaces) and specific context (i.e., COVID and 3D printing) and then using Boolean operators to combine the terms [40]. The chosen search terms were refined using iterative scoping searches of several dozen articles to identify common terms and synonyms keywords, a process recommended in guides for systematic literature reviews [40]. We observed that "3D printing" was the most frequently used phrase to represent AM technologies, presumably since the most common audience of the articles was the general public. The searches were conducted in November and December of 2020. These search terms resulted in many extraneous results that were not relevant to our research objectives. To screen search results to identify organizations to include in our list, we utilized formal inclusion and exclusion criteria [40]. Inclusion criteria included: 1) organizations not typically involved in PPE production; 2) active in response to COVID-19; 3) used AM technology to produce PPE (e.g., face shields, face masks) or medical devices; and 4) design or manufacturing process explicitly described in the article. Exclusion criteria included: 1) organizations outside the US and 2) repeated articles covering the same organization's effort.

Articles were coded for inclusion, i.e., judged based on their title and text whether the article fit the inclusion criteria and therefore should be retained or discarded from further

analysis. Two researchers performed half of coding each to reduce load on any one coder [40]. Although formal analysis of reliability is not required in systematic reviews [40], to ensure the screening decisions of each coder were reliable, the interrater reliability for inclusion was tested after the coding was complete, using a random sample of 50 search results. Calculating and reporting interrater reliability can improve the rigor of a systematic review [40]. The interrater reliability, measured using Cohen's kappa, was found to be equal to 0.76, indicating substantial agreement [41].

The stopping criteria for our search was identifying a maximum of 150 efforts using the search method described above. For exploratory studies using nonprobability sampling [42], a sample size ranging from 20 to 150 individuals is suggested as a rule-of-thumb. Given that a recent summary of typical survey response rates for email reported an average of 55% for contact by email [43], we sought to identify 150 efforts in order to end up with approximately 85 responses (the mean of the suggested range for exploratory studies). Ultimately, 145 efforts were identified following the article inclusion process outlined in Fig. 1.

After an article was selected for inclusion, it was read by at least one researcher to identify relevant information, such as the size of the effort, reflected by the number of printers and production rate, and what specific type of PPE was produced. The goal of this high-level review (reported in Section 4.1) was to investigate the extent of efforts undertaken by makerspaces and universities. While the published news articles helped provide an overview of the different efforts conducted across the US, these articles contained different types of information insufficient for a detailed analysis of all reported efforts. To systematically investigate these efforts, we created an online survey to collect detailed information from individuals involved in all 145 efforts. In doing this, we emailed 186 individuals whom we identified as participants in these efforts, with a request to complete our survey. It should be noted that if a news article identified multiple people involved in the production effort at the same organization, we emailed all of them. The results of this survey allowed for a much more detailed analysis of the community efforts to create PPE in response to the COVID-19 pandemic.

The survey was designed following common guidelines for effective survey development. We predominately collected factual data using close-ended questions to improve the reliability of respondents answering questions and the reliability of the research team interpreting answers, and to allow for easier grouping of respondents into common categories [44]. Several open-ended questions were also included to collect some qualitative data. To increase the validity of factual reporting, we used well-established effective survey design practices such as defining terms and using an anonymous self-reporting format [44]. The survey contained 12 closed-ended research questions that created interval data (e.g., respondents chose between answers of 20 hours per week or less; more than 20 hours but less than 40 hours per week; or more than 40 hours per week to answer the question "Roughly how many hours per week did each person on your team work on the production efforts?"). Eighteen questions created nominal data (e.g., respondents selected from PLA, ABS, PETG, or other to answer the question "What type of feedstock material did you use to make your parts?"). The questions were ordered in sections based on similarity, and sections were ordered so that straightforward, closed-ended questions occurred first, followed by more complex and open-ended questions. We used peer review to check for content validity of the questions we included, included introductory material with instructions and informed consent information, and piloted the survey with several
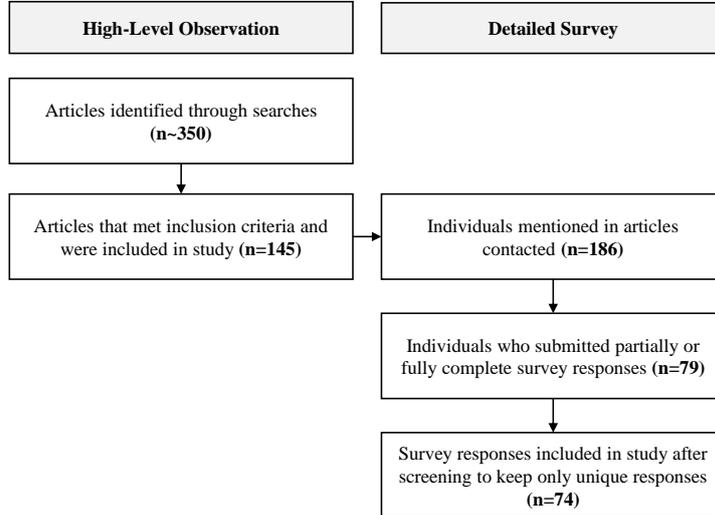
Figure 1: Flow chart for inclusion in our study.

users before releasing the survey to respondents, as recommended in common guidelines [44, 45].

The survey was created and distributed as a Qualtrics survey. The goal of this survey was to investigate the PPE designs, production logistics, and AM processes employed by makerspaces and universities, and to explore connections between these variables and the success of the effort, measured by production rate and by self-reported success. By identifying variables that seem correlated with effort success, we can form recommendations to improve future emergency response efforts using AM. The survey was divided into five sections with goals of: 1) understanding the different practices adopted for the PPE design process; 2) summarizing the logistics of the production effort; 3) exploring adopted AM process specifics such as process parameters and support material; 4) identifying utilized packaging practices; and 5) evaluating the success of the effort. For more specific details, the survey is included as an appendix to this study. While most efforts involved other manufacturing processes in addition to AM to produce some parts needed for the PPE assembly, our focus was on components made using AM only. Analysis of the survey responses is reported in Section 4.2.

A total of 79 out of 186 individuals responded to our detailed survey, corresponding to a response rate of 42.5% (excluding any individuals who answered less than 25% of the survey). Some of these individuals were from the same organization. Different individuals sometimes oversaw the production of different PPE types or worked from different production spaces at the same institution. In other cases, multiple individuals worked together to oversee the same part production in the same space. Responses from individuals at the same organization were analyzed to evaluate similarity. We observed that 5 individuals described duplicative efforts as other individuals who also responded to the survey, and so their responses were consolidated into one response. In this way,

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we eliminated duplicated responses and created a set of 74 unique responses.

4. Results

As described in the previous section, our study involved two stages. First, we conducted an overview survey of 145 community-driven efforts identified from news articles and involved participating organizations' websites. This survey led to a high-level observational analysis of the efforts conducted across the US which is reported in Section 4.1. Section 4.2 reports the main results of this study, namely the analysis of the responses we received to our detailed survey that capture specific production details from 74 individuals who were involved in a wide variety of different responses.

4.1. High-level observational analysis

The 145 identified efforts were led by different types of organizations including 105 universities (73%), 31 makerspaces (21%), and 9 local libraries (6%). They were located throughout the US, in major cities such as New York City, NY and Los Angeles, CA as well as smaller cities such as Portsmouth, NH and San Angelo, TX. Figure 2 shows that efforts were initiated at organizations in most states, even in states where few cases had been reported (log color scale indicates COVID-19 case counts in each state as of April 30, 2020 per 10,000 residents, using data provided by the CDC [46] and the US Census Bureau [47]). Positive correlations were identified between the number of production efforts in each state and the state population (Spearman's $\rho=.68$, $p<.01$), the number of production efforts and the total case count in the state ($\rho=.66$, $p<.01$), and the number of production efforts and the case count per 10,000 residents ($\rho=.39$, $p<.01$).

During the period of emergency medical supplies shortage, 81% of the identified efforts produced face shields, while 7% only produced masks, 10% produced both masks and shields, and 2% produced only other products such as ear savers, PAPR clips, ventilator moisture trap, and splitters for ventilators. In our analysis henceforth we focus on face shields and masks because they were the most frequently produced through community-driven efforts.

For manufacturing, some organizations designed face shields themselves and got approval from regulatory organizations for production and distribution. Some organizations adopted designs of face shields that were shared online, either directly or after some modifications. In the 145 news articles we identified, the specific face shield design used for printing was mentioned in 43 articles. Nine articles only mentioned that an NIH-approved design was used without mentioning any specifics. Some efforts produced shields of multiple designs. The face shield designs (examples show in Fig. 3) that were specifically mentioned include Prusa, 3DVerkstan, Budmen, Design that Matters, and other specific designs, with the Prusa design being the most popular (Fig. 4-a). Many of these designs were available via the NIH 3D print exchange [48]. The 3D-printed visor component of the face shield would hold a clear plastic shield in place on the user's head. The adopted mask designs mentioned in our studied articles included Montana Mask, Copper 3D, and La Factoria.

To better understand the timing of organizations' responses, we plotted the number of news articles by their date of publication. Figure 4-b shows that most of the efforts started by the last week of March and persisted throughout April, indicating that their
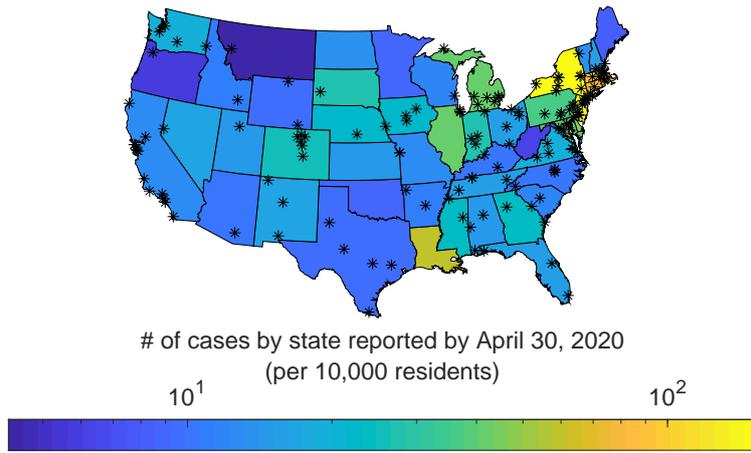
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Figure 2: Distribution of organizations involved in COVID-19 PPE production using AM in the continental US, with case counts of states per 10,000 residents displayed as color on a log scale.
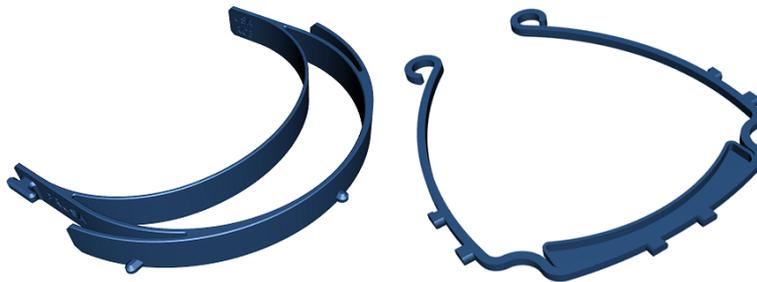

Figure 3: Prusa and 3DVerkstan face shield visor designs available from NIH 3D Print Exchange [48].
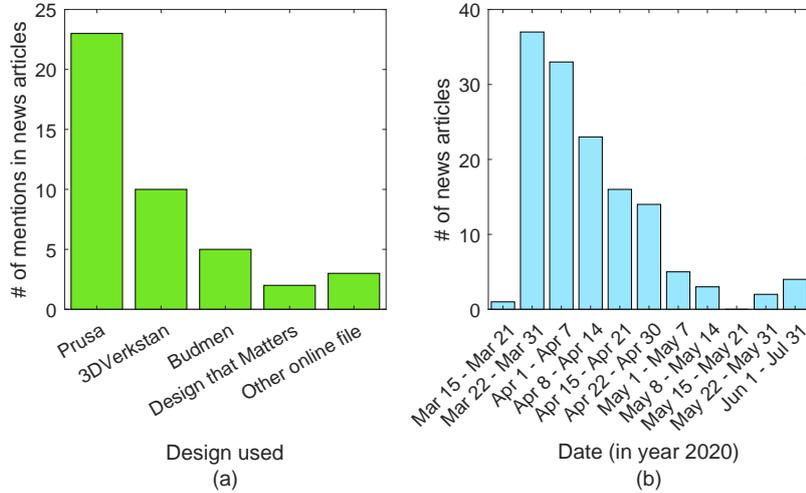
Figure 4: (a) Prusa was the most common shared design file that was adopted; (b) Publication of news articles describing community-driven responses peaked in late March, 2020.

response started with the surge in PPE demand in March and continuing until the traditional supply chain was restored. In case of a missing publication date in any article, we assumed the date based on their first shipment or delivery date.

Among the efforts we identified, 37 organizations mentioned the number of AM machines they used to produce emergency medical products. The number of printers used by each effort ranged from 1 to 100 with a median of 12 (Fig.5-a). Eighteen organizations mentioned the total number of face shields produced using AM. This number ranged from 40 to more than 6000. The face shield production rate was mentioned by 53 organizations. Some mentioned the rate per day whereas some mentioned the rate per week, so for convenience, we converted production per week to production per day, assuming production ran 7 days per week. The production rate ranged from 6 to 1000 shields per day with a median of 80 shields per day (Fig.5-b).

4.2. Detailed survey results

Individuals who were identified using the news articles, as described above, were contacted and invited to complete our survey. Their responses were anonymous. Individuals who were eligible to be surveyed included people who were directly mentioned in news articles highlighting responses to COVID-19 shortages involving design and production of PPE using AM, which was most frequently staff and volunteers at universities, makerspaces, and public libraries. Faculty and students involved in efforts at universities were also commonly mentioned. Individuals for whom we could not identify an email address were not contacted. Some of the survey responses did not include responses to every survey question but we still included data from answered questions whenever applicable. In some cases, respondents selected multiple responses instead of a single response and so the frequency counts reported in our analyses below do not always sum to the total number of unique respondents. The survey results are grouped into four subsections: 1)
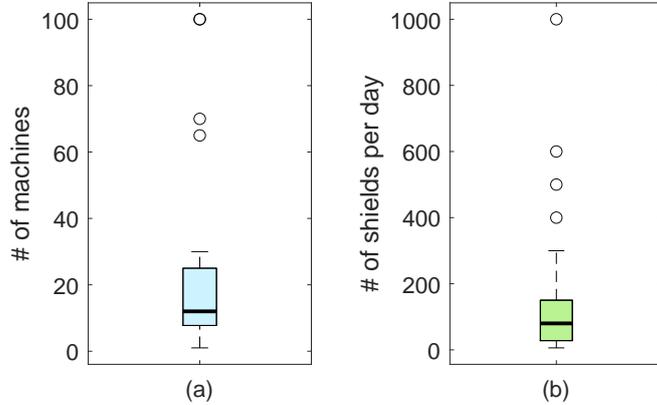
Figure 5: (a) Number of AM machines across 37 organizations; (b) Number of face shields per day across 53 organizations. Horizontal lines in each box indicate median values, box edges indicate the 25th and 75th percentiles, whiskers indicate the most extreme data points not considered outliers, and circles indicate outliers.

part design process; 2) effort logistics; 3) specifics of the AM process; and 4) evaluation of effort success.

4.2.1. Part design process

The type of PPE created by survey respondents matched trends observed in the larger population of efforts (145 news stories), reported in Section 4.1, with face shields being the primary type of PPE produced by 90% of respondents (n=66) and 9% of respondents (n=7) primarily producing face masks. Most respondents, 85% (n=63), used or adapted an online CAD model, while 15% (n=11) created their own model. The designs that respondents reported using matched those reported by the larger population described in Section 4.1, with versions of the Prusa face shield design being the most popular (n=24). Of the respondents who used or adapted an online model, 42 respondents reported making design changes, while 17 reported making no design changes. Most of the design changes described were minor (e.g., removing or adding a logo) or related to adjustments in print quality or speed. Some respondents made design changes to improve comfort or usability for the end-user.

Many respondents who adapted an online model or created their own model solicited feedback from the end-users of their parts about the functionality of the design. The most common end-user of the PPE produced by survey respondents were hospital workers, followed by other health care workers (Fig.6-a). Feedback from the end-user was most frequently obtained both during design and after the PPE was delivered (n=24), while some respondents obtained feedback only during design (n=20), some respondents obtained feedback only after delivery (n=13), and some users did not obtain any feedback (n=11). While the most common source of design feedback was end-users of the PPE, one respondent reported receiving feedback from state officials on their design.

The total number of reported design iterations (defined in the survey as changing the CAD file and reprinting the part) varied from 0 to 27 (Fig.6-b). Most feedback received
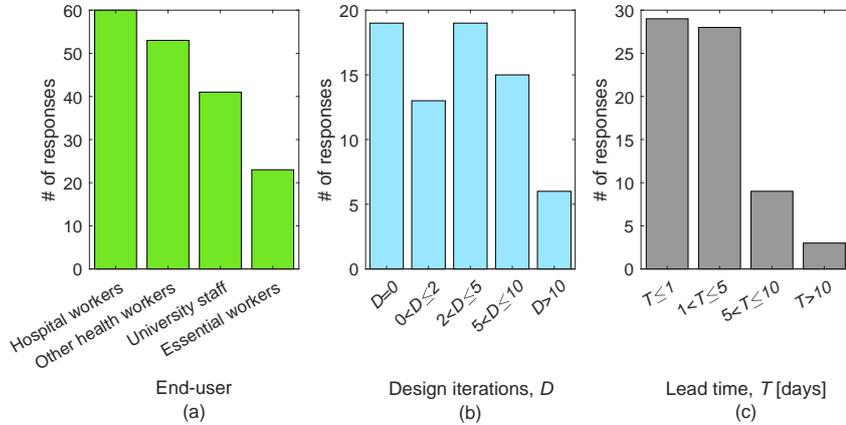
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Figure 6: Most respondents reported (a) producing PPE for hospital workers, (b) completing a number of design iterations, and (c) having lead times of greater than one day.

during the design process involved wearability and functionality. Five respondents reported having to iterate on features regarding the top of the face shield headband (e.g., "We were asked to include a roof over the top to prevent droplets coming in front of face shield"). Feedback obtained after delivery was generally positive, with reported responses of end-users such as, "They loved the use, it met their need during the time, and people reused it multiple times due to the comfort level." Several respondents received feedback that while their designs were not perfect and had some issues with functionality or comfort, the end-users were glad to have a solution before PPE was available through traditional supply chains again.

Respondents described incorporating design feedback from the end-user and making corresponding changes to the CAD model to ensure successful printing of the new design. Additional tasks, such as organizational approvals and finding adequate staff and equipment to begin production, were also described. Despite these demands, respondents reported relatively short lead times (defined here as the time between deciding to start PPE production and when the first part was successfully produced) that ranged from less than one day up to two weeks (Fig.6-c). Respondents who created their own CAD models tended to have slightly longer lead times and more design iterations than those who adapted an online model. The lead times and the number of design iterations were similar between respondents who used the Prusa and 3DVerkstan models.

4.2.2. Effort logistics

Most respondents packaged their PPE for delivery ($n=56$, compared with $n=12$ who did not). The most common packaging supplies were plastic bags and boxes. The number of units in a single package varied widely from 5 to 300. The time required for the packaging process had a similarly large range, from less than 1 minute per package up to several hours. Three respondents reported sterilizing their PPE as part of the packaging process. Once packaged, different efforts used various methods to distribute PPE such as delivery to the users' location ($n=52$) and having a representative from the end-users pick the parts up ($n=35$). Five respondents reported partnering with external

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organizations such as a state government agency to handle distribution.

The size of efforts varied widely where the number of individuals involved in each production effort varied widely (Fig. 7-a) and ranged from 1 to 400. Very large efforts were not uncommon, with 4 respondents reporting more than 100 individuals involved. Compensation varied, with 20 respondents reporting the individuals involved in the effort were paid, while 50 reported paying none or only some of their team members. The number of printers used simultaneously ranged from less than 6 up to a maximum of approximately 1000 printers (Fig. 7-b). Respondents who reported having dozens of people involved also tended to have dozens of printers running simultaneously. These large efforts tended to be a spoke-hub production model, with a centralized production center at a university or makerspace that distributed instructions and collected finished parts and dozens of printers that were owned and operated by volunteers from distributed locations such as their homes. We identified 14 respondents who utilized some form of a spoke-hub production model and each one utilized at least 12 printers simultaneously. This was not the only production model that utilized many printers: 3 different efforts utilized more than 30 printers in a centralized location, each with less than 10 dedicated staff members.

The number of units of PPE produced varied widely as shown in Fig. 7-c. In addition to choosing a categorical interval as shown in Fig. 7-c, we asked respondents to provide the approximate number of parts they made per day. From 44 responses to this question, the number of units produced per day ranged from 8 to 1000 with a median of 77.5, which closely corresponds to the median for the larger population of efforts surveyed in Section 4.1. If we separate data from the spoke-hub production model, the median number of units produced per day is 125 (n=10) while the median for other efforts is 47.5 (n=34), a significant difference according to the Wilcoxon rank sum text (p=.03). We also calculated the number of units produced per day per printer to estimate the efficiency of production (using the median of the reported printer range when the exact number of printers was not available). The spoke-hub efforts had lower units per day per printer (median was 2.18, n=10) compared with the other efforts (median was 5.33, n=33), a significant difference according to the Wilcoxon rank sum text (p<.01).

4.2.3. Printing process specifics

The most common AM technology used was Fused Filament Fabrication (FFF) (n=68) although a few respondents used some form of Stereolithography (SLA) (n=3). Most FFF machines that were identified as being used in this effort were desktop machines with retail prices ranging from \$200-\$5,000, from companies such as Prusa and Ultimaker (Fig. 8-a). Industrial printers such as Stratasys Fortus machines were less common and were mentioned by only two respondents. Because most of our respondents used FFF, the production rates reported in Section 4.2.1 are indicative of the average capacity of the FFF technology. One notable outlier was a production rate of 1000 reported by a respondent who oversaw an effort that utilized a new high-production-rate version of SLA. While one respondent who used FFF also reported a production rate of 1000, the production rates for efforts using FFF were typically smaller. To investigate FFF production rates in more detail, we excluded SLA data to evaluate the correlation between production rates and the number of printers (the median of the reported printer range was used when the exact value was not available). A positive correlation (Spearman's
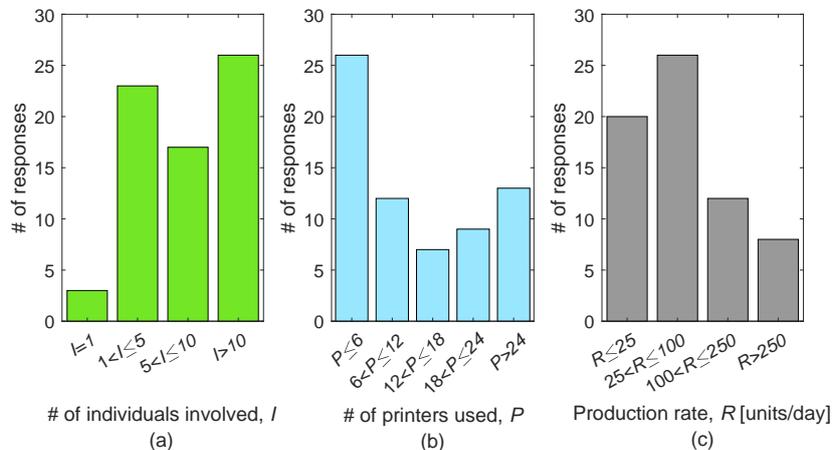
Figure 7: The (a) number of individual people involved; (b) number of printers used; and (c) production rate varied widely.

ρ=.78, p<.01) was identified for FFF data, indicating that efforts with more printers tended to print more parts per day than efforts with fewer printers.

A large portion of respondents (n=22) reported using several different types of filament in their production efforts. The most commonly reported filament types were PLA, PETG, and ABS (Fig. 8-b). Issues sourcing filament (e.g., shortages, long lead times for delivery, and price increases) were reported by 13 respondents for both PLA and PETG. Production costs, which were presumably driven by material costs, ranged from about $2 to $20 per unit, but most respondents reported costs under $5 per unit ($n$=51). Two respondents reported finding it difficult to estimate costs because they used materials they already had in stock or had materials donated to them. Because so many efforts used multiple types of filament but only reported a single average cost per unit, we could not identify differences in production cost associated with different filament.

About half of the respondents (31 out of 68) reported having difficulty with identifying the right process parameters to produce their designs. Two respondents described using the process parameters that were recommended by the developers of the design they used, such as those provided by the NIH file exchange. But for most of our respondents, the specific process parameter settings utilized (e.g., layer thickness, type of bed adhesion, and infill percentage) varied widely. Several respondents (n=9) reported adjusting printing settings throughout their production process to either improve quality or increase their production rate. Using different types of material in one effort required changing printing settings, with PETG reported as being especially difficult by two respondents. Another common problem reported was having to adjust printing settings for each printer when utilizing several different machines, which caused difficulty for novices involved in spoke-hub production efforts (e.g., "Communicating settings to a loosely organized team of individuals with random 3D printers caused much confusion."). Three respondents who oversaw a spoke-hub production system mentioned setting up an online message board or website with information for volunteers about printing problems and
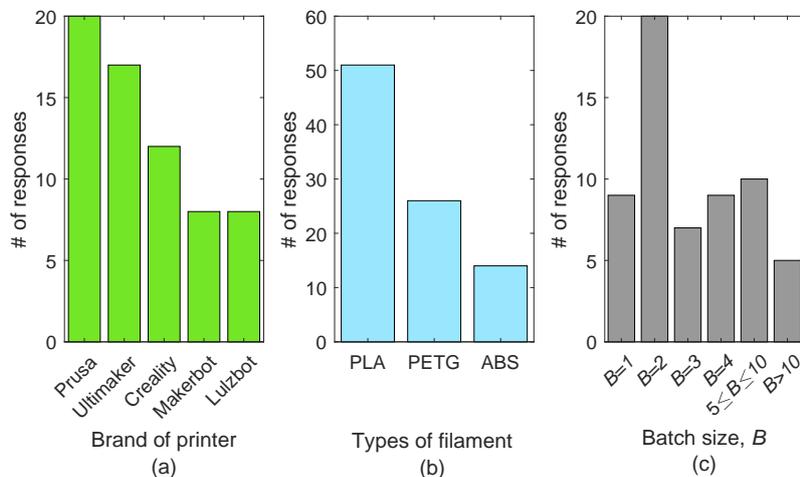
Figure 8: (a) Prusa was the most common printer brand; (b) PLA was the most common filament; (c) Most respondents reported batch sizes of four or fewer parts

selection of process parameters.

Most respondents printed multiple parts on the build plate at a time. The exact number of parts that could fit on the build plate depended on the printer bed size, part design, and configuration of parts chosen by the user. For respondents who used multiple printers, because the number of parts printed at once varied, some respondents reported a range, and so we took the median of the range they reported. The reported batch sizes are shown in Fig. 8-c. The batch sizes ranged from 1 to 36 and with a median of 3. The specific design produced impacted the batch size, with 4 out of the 5 users who reported batch sizes greater than 10 reported using the 3DVerkstan model which was low profile and easy to stack so many duplicates could be printed at once. Unsurprisingly, the batch size was correlated to the time required to print each batch (Spearman's ρ=.61, p<.01). The time required for printing each batch ranged from less than 1 hour to 48 hours. There was no clear correlation between batch size and production rate.

Print quality was a challenge for many, with 58 respondents reporting having parts fail during printing or having parts printing with unacceptable quality, while 8 respondents reported no problems. We asked respondents to estimate the failure rate associated with these problems. Reported rates ranged from 1% to 20% and the median rate was 5%. Common problems included build plate adhesion, print head issues, and filament quality issues. Several respondents involved in the spoke-hub production models reported that failure rates for parts produced by volunteers were significantly higher than what they observed in their own production. Support material removal caused additional issues. Many respondents did not use any support material (n=46), but those who did (n=21), reported having to throw out several parts due to damaging the parts during the removal support material (median failure rate was 5%). The processing of dissolvable support material took longer than manual removal of support material.

4.2.4. Evaluation of effort success

The vast majority reported that their efforts were successful, with 99% (67 of 68) of respondents rating their efforts as moderately successful, very successful, or extremely successful. There appeared to be a correlation between production rate and self-reported success. The median production rate of respondents who rated their effort as extremely successful was 150 units per day (n=23), the median for efforts rated very successful was 100 (n=13), and the median for efforts rated moderately successful was 24 (n=7). Respondents who used a spoke-hub model tended to rate their efforts more favorably than the rest of respondents, with 79% (11 of 14) selecting extremely successfully, compared with 45% (24 of 53) of other respondents,, a difference that is statistically significant according to a Fisher's exact test (p=.036).

We asked survey respondents about barriers they encountered in their production efforts. Three respondents had difficulty finding organizations that would accept their PPE, especially masks, with one respondent reporting "the approval process for some hospitals is ridiculous. We have some places that took several months, some outright rejected them." Navigating the bureaucracy for staffing informal production spaces was also cumbersome, with difficulties reported such as, "Permission to access campus during a statewide lockdown," and "only a very few people were able to help out regularly." In addition to challenges sourcing filament, eight respondents reported having issues sourcing material for the clear plastic attached to the face shield headband, which was typically cut using laser cutting. Another barrier was production speed where three respondents reported that the slow production speed of 3D printing or laser cutting was problematic. A final common barrier was lack of experience, with one respondent stating, "We are very much amateurs so getting the settings on the 3D printer correct was very difficult for us."

There were two interesting trends related to overall production that should be highlighted. The responses to many questions in the survey had clear distinctions between respondents who oversaw production in one central facility, and respondents who oversaw production in a spoke-hub model. Some of our survey questions were difficult for those involved in spoke-hub production to answer, such as questions regarding process parameters or batch size, because they varied widely. Similarly, our survey did not necessarily capture all relevant efforts which focused on using AM as a prototyping method that was then used to guide mass production using a different process. However, several respondents (n=6) mentioned using AM as a bridge to different production technologies to increase production rates, such as injection molding, CNC routing, and vacuum forming. These trends will be discussed in further detail in Section 5.

5. Discussion

The results of this study indicate that there was substantial variability in how makerspaces and universities mobilized to respond to shortages of PPE. Many utilized existing designs that were shared online, which was associated with shorter lead times before beginning production. The specifics of their production methods varied widely, with production models ranging from centralized production with a few dedicated staff to hundreds of individuals contributing from distributed locations. Most used FFF, but the batch size, printer cost, and the number of printers varied widely. Production efficiency

varied widely, with many efforts requiring individuals to be ready to adjust process parameters, deal with printing failures, post-process parts, and package and deliver parts. One constant across most efforts, however, was the feeling of success and positive feedback from health care and other essential workers who appreciated having any PPE to meet their immediate needs.

In the following subsections, we discuss our study limitations, and then interpret the findings of our study, focusing on how our results build on the knowledge about AM community-driven responses to PPE shortages from existing literature. We identify areas of success as well as areas where improvements could be particularly impactful for improving future emergency-driven applications of distributed manufacturing using AM. We have highlighted five recommendation areas, discussed below, and we draw connections between our recommendations and recommendations that have been mentioned in the existing literature.

5.1. Study limitations

Because of the emergent nature of the AM response to the COVID-19 pandemic and the lack of research focusing on quantitative data elicited directly from individuals who participated in community-driven efforts, this study was exploratory in nature. Themes were not identified a priori from existing research, but instead evolved during the analysis of our results. Our findings can guide further follow-up studies, to confirm our findings using a larger sample of individuals.

The results of our study may reflect some biases from how we collected data. The individuals who answered our survey are not a random sample of individuals who participated in community-driven responses, since they opted to participate. The search process to identify efforts and the individuals involved with efforts was conducted using Google searches, so we were more likely to identify efforts that were well-publicized. The Google searches were conducted without specific efforts to control personalization bias, but a test of the influence of personalization bias showed that 2 out of 100 searches were impacted, indicating personalization bias was not a significant factor in our searches. The data we collected was self-reported, so there may be some biases in respondents' responses, especially for more qualitative measures such as effort success.

5.2. Advantages and limitations of AM

In our survey of existing literature, we identified several advantages of AM that were highlighted to explain why AM was adopted in response to PPE shortages, namely: reduced workforce needs, fast prototyping and production, ease of part redesign, and an ability to produce a wide range of parts. Survey respondents did make use of untrained labor (e.g., volunteers in the community) and were able to prototype rapidly. But our results showed that many efforts ultimately focused on mass production using AM, with widely varying production rates. To make effective policy changes and recommendations about emergency production, it is necessary to estimate the potential scale of different production methods. In the US, there are approximately 250 active community makerspaces, according to one database [49], and around 150 university makerspaces, [50], totaling approximately 400 makerspaces. In a future emergency, we could optimistically assume that each makerspace could coordinate the production of 1,000 units per day (the maximum we observed) for a total production of 400,000 parts per day. Depending on

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the production model employed by each makerspace, this national effort might involve anywhere from 3,000 to 160,000 individuals. For comparison, if another manufacturing technology, such as injection molding was used, one molding machine could produce approximately 4,000 units per day [51]. In this case, only 100 machines would be needed nationwide to match the AM production rate of 400,000 parts per day. If we assume a staff of 5 is sufficient for each molding machine operation, this effort will involve 500 individuals.

Data regarding achievable production rates with community-driven AM should be considered when planning for future emergencies at the local level (universities and hospitals) and when making decisions regarding PPE stockpiling. Survey results reported here provide estimates for achievable outcomes that could help individuals and organizations more objectively assess the impact of their potential response to future production shortages. We observed short lead times for AM efforts, with only a few days between project initiation and production. Other technologies, such as injection molding using aluminum molds, may have lead times that are only slightly longer [51]. Decision makers should communicate the limitations of AM, such as high scrap rates, the need for frequent manual intervention, issues with part quality, and high cost per unit to ensure a plan is made to transition from AM to more efficient production technologies. Multiple technologies could be considered for emergency production, with AM meeting an immediate need, followed by more efficient but still short-term production (e.g., injection molding with aluminum molds) before traditional mass manufacturing can be restarted. Other studies, [2], have recommended hospitals to consider setting up their own production facilities. While that may be beneficial, decision makers should consider AM's limitations regarding required experience, production rate, cost, and efficiency. **Recommendation 1: Make strategic decisions based on an understanding of the scale and limitations of informal production efforts.**

5.3. Summary of AM efforts

Prior literature has surveyed AM production efforts that were conducted in response to COVID-19, but not with enough detail to understand quantitative differences in production efficiency. From our survey responses, it was clear that a variety of production models were employed with different numbers of staff and printers. The highest production rates were achieved with the spoke-hub model and the high-productivity centralized production model. The spoke-hub model was efficient in that it avoided unnecessary duplication of effort by standardizing design choices, buying materials in bulk, and setting up streamlined distribution. Groups utilizing this model were able to leverage many distributed printers and individuals for a common goal, leading to high production rates. Downsides included lack of quality control, confusion over proper process parameters, and low productivity on a per-printer basis. The high-productivity centralized production model focused on production at one or two central locations with a large number of printers, such as a well-equipped university makerspace, or a few printers capable of high production rates. Benefits include a small staff and the ability to control process parameters and quality more closely. **Recommendation 2: Identify and recommend efficient production models.**

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5.4. Comparison of different designs

Existing literature has described differences between different PPE designs in terms of functionality [21, 35] and the time required to manufacture [33]. Most survey respondents reported eliciting user feedback to improve their designs, but more rigorous tests of functionality were not mentioned, perhaps because so many respondents used models from design repositories rather than developing designs from scratch. Sharing CAD files for different designs of PPE was a highly effective practice in this pandemic. Most efforts utilized a shared design, and it appears that this practice shortened lead times and led to fewer design iterations. However, many respondents reported adjusting designs to improve printability and printing speed. Original designers could improve the impact of their shared designs by optimizing their designs in a manner that balances printing speed with print quality, which would minimize duplication of efforts from individuals at makerspaces needing to make those adjustments. More design documentation, describing why design decisions were made, could also help makerspaces understand the benefits of the design in its current state and would clarify to what extent the functionality of the design has already been verified.

We observed large variations in the production rate and efficiency of different efforts, but these differences were not entirely explained by choice of design. While there is a clear interaction between choice of design and batch size (e.g., it is easier to print large batches of the 3DVerkstan design than the Prusa design), not all efforts chose to print large batches. Design documentation for shared designs should also include tips on improving printing efficiency, such as recommended number of units to print at once and how to avoid support material. A related recommendation to integrate pre- and post-processing decisions into the AM process for PPE has previously been proposed [13].

Future efforts should also focus on ways to minimize variability in product quality that results from differences in printer type, process parameters, and filament type. Based on survey responses, different printers produced parts with widely varying quality, a limitation which has previously been mentioned in existing literature [18, 24]. Process parameters were difficult to recommend, especially for spoke-hub models where hundreds of different printers were utilized. Although others have recommended more substantial testing of the functionality and safety of community-produced PPE [15, 16, 25, 26, 32], we go further to suggest that PPE designs should be printed on a wide variety of printers and their functionality tested to see if some designs are not compatible with certain types of printers or filament. This testing process could be done in collaboration with makerspaces and universities, or by a government agency. Online repositories like the NIH file sharing site, or new repositories hosted by NIST or America Makes, could illustrate the production of popular PPE designs, and recommend detailed process parameters for each specific design, material, and printer type. Finally, these design repositories should provide advice about quality control targeted at community-based production efforts, such as simple guidance about sampling a certain number of produced parts for strength or rigidity. ***Recommendation 3: Include guidance on variance due to printer type, process parameters, and filament type when sharing 3D-printable models.***

5.5. Production challenges

A few survey respondents recognized AM's limited production rate and identified industry partners to scale up production using non-AM techniques. However, this did not appear to be common practice, and several groups scaled up production by themselves. While we recognize that mass production may not be a goal of all groups that participate in community-driven efforts, AM has the potential to be an effective bridge to more effective mass production processes in response to supply chain disruption [10]. However, this transition can be difficult to facilitate for those who are used to makerspace production technologies. Efforts to scale up production could be made more efficient through partnerships with existing manufactures or manufacturing experts. Coordinated connections between makerspaces, universities, and industry, could also help with supply chain issues by connecting makerspaces with new suppliers or redirecting materials for emergency use. Organizations such as Manufacturing USA institutes and NIST's Manufacturing Extension Program can help coordinate such connections. ***Recommendation 4: Improve collaboration between community efforts and the larger manufacturing industry.***

We identified makerspaces and universities across the US that were able to respond to their community's needs for PPE. The connection between makerspaces, universities, and their communities enabled efficient prototyping and allowed for customization of PPE to meet the needs of local end-users. After production, PPE could be distributed quickly to locations in the community. However, survey respondents identified some issues with local distribution, such as finding end-users who would accept their PPE. We also observed that more populous states tended to have more production efforts, indicating that such states may be better equipped than less populous states to use community-driven production in future emergencies. Partnering with government agencies and non-profits for distribution was mentioned by some of the respondents as an effective strategy that should be scaled up in the future. National organizations such as the Red Cross could also serve as a centralized system to identify where there is a need for parts, on a national basis, so production groups do not end up with un-used PPE, as was reported by some respondents.

Most groups worked independently of each other, with only local collaborations and communication between different production groups. Creating a regional or national organizational structure to support community-based production could help coordinate and prioritize the distribution of raw material, such as filament, so individual groups are not forced to compete for supplies. Larger organizations could also stockpile materials for future emergencies, as recommended by Kunovjanek et al. [19], but this must be done cautiously as some respondents reported quality problems when using old filament that had been donated. Regional or national organizations could also help with communication between disparate groups to help prevent duplicative efforts (e.g., in our survey of news articles, we observed that some university groups initially worked independently of others at their university). Central communication hubs also appeared to be beneficial for debugging printing problems. Several respondents reported benefiting from setting up communication channels like Slack, especially for distributed spoke-hub efforts. A case study of Germany's community-driven response to PPE shortages during COVID-19 indicates that they had robust central communication [52], so specifics of their implementation could be explored and duplicated. ***Recomendation 5: Leverage distributed manufacturing strengths while still connecting distributed sites.***

6. Conclusion

The COVID-19 pandemic led to shortages of PPE throughout the world and in the United States, prompting community-driven production of PPE using AM. We analyzed 145 publicly available news stories and surveyed individuals who participated in 74 different production efforts to understand how makerspaces and universities mobilized to respond to the PPE shortage. Survey results provided estimates of lead times and production rates that will help to set expectations for future community-driven manufacturing efforts that utilize AM. Community-driven efforts were able to ramp up production quickly and iterate on their designs based on feedback from the specific needs of end-users in their local community. We identified that the median production rate of community-driven AM efforts was 77.5 units per day, a production rate that is much lower than potential production rates of traditional manufacturing processes. This does not mean that community-driven AM production was unsuccessful but does highlight the benefits of collaborating with local industry partners to scale up production using non-AM methods in parallel to beginning AM efforts to maximize production. Based on survey responses, we observed that the spoke-hub production model had higher production rates and was characterized as more successful by those involved than efforts that had more centralized production. However, the selection of appropriate process parameters and variations in print quality achieved by different printers and makers were common barriers with this production model. Since many groups took advantage of shared CAD files available on public websites, design documentation that includes guidance on how to improve printing efficiency and verify part quality/functionality could help eliminate these common barriers. While we focused on areas where improvements could be made, it is encouraging that nearly all surveyed individuals characterized their group's effort as successful, which is promising for future community-driven use of AM in response to emergencies.

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