Rapid Response! Investigating the Effects of Problem Definition on the Characteristics of Additively Manufactured Solutions for COVID-19

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Designers from around the world have proposed numerous engineering design solutions for problems related to the COVID-19 pandemic, many of which leverage the rapid prototyping and manufacturing capabilities of additive manufacturing (AM). While some of these solutions are motivated by complex and urgent requirements (e.g., face masks), others are motivated by simpler and less urgent needs (e.g., hands-free door openers). Previous research suggests that problem definition influences the creativity of solutions generated for the problem. In this study, we investigate the relationship between the definition of problems related to the COVID-19 pandemic and the characteristics of AM solutions that were openly shared for these problems. Specifically, we analyze 26 AM solutions spanning three categories: (1) hands-free door openers (low complexity problem), (2) face shields (moderate complexity problem), and (3) face masks (high complexity problem). These designs were compared on (1) DfAM utilization, (2) manufacturability (i.e., build time, cost, and material usage), and (3) creativity. We see that the solutions designed for the high complexity problem, i.e., face masks, were least suitable for AM. Moreover, we see that solutions designed for the moderate complexity problem, i.e., face shields, had the lowest build time, build cost, and material consumption. Finally, we observe that the problem definition did not relate to the creativity of the AM solutions. In light of these findings, designers must sufficiently emphasize the AM suitability and manufacturability of their solutions when designing for urgent and complex problems in rapid response situations. [DOI: 10.1115/1.4052970]

Keywords: design for additive manufacturing, problem definition, creativity, COVID-19, creativity and concept generation, design evaluation, design for manufacturing

1 Introduction and Motivation

The COVID-19 pandemic has imposed unprecedented challenges around the world. The rapid transmission of the virus and the sharp increase in the number of cases has imposed tremendous pressure on hospitals and healthcare providers as global supply chains experience untold disruption. The acute shortage of personal protective equipment (PPE)—necessary for frontline healthcare workers to battle the pandemic—has been one of the most critical challenges imposed by the pandemic [1,2]. To overcome this shortage, in March 2020, the World Health Organization [3] called for industries and governments around the world to increase their PPE production by 40%, with a special emphasis on surgical masks, examination gloves, and goggles.

Additive manufacturing (AM) processes offer designers the ability to rapidly design, prototype, and build design solutions. Motivated by this capability to facilitate rapid manufacturing, several designers have proposed PPE designs that can be additively manufactured [4–6]. Moreover, designers have proposed PPE solutions that leverage AM capabilities such as mass customization and part consolidation. For example, Kursat Celik et al. [7] discuss the design, prototyping, and testing of an AM face shield, wherein, they use Design for AM (DfAM) techniques such as part consolidation to reduce part count and to reduce print time and material usage to expedite production. Similarly, Amin et al. [8] present techniques to optimize the build on desktop material extrusion processes to maximize the production rate. Bishop and Leigh [9] further demonstrate that large-scale AM processes can be used to make face shields at much higher production rates and can achieve production rates similar to injection molding. Swennen et al. [10] discuss the design of face masks that can be mass-customized using AM to better fit the user and facilitate reusability. Similarly, Erickson et al. [11] use AM parts to retrofit surgical helmets into respirators, and Ayyıldız et al. [12] discuss the design of an AM ventilator output splitter that can be used to serve multiple patients with fewer ventilators. Finally, Pearce [13] reviews the various open-source ventilator solutions made available through the democratization of design.

All of the solutions discussed so far have been developed for critical and urgent problems and are essential for the battle that healthcare workers are facing on the frontlines of the pandemic. Failures in the functioning of these solutions (e.g., face masks) could (1) result in an unchecked spread of the virus and (2) put essential healthcare workers at risk of exposure to the virus. Therefore, designers, manufacturers, and suppliers must work in tandem with medical and healthcare experts and environmental health and safety personnel to ensure that solutions developed for critical problems are appropriately vetted for their safety [14–17] and satisfy the complex regulatory pathways required for approval [18,19].

The rapid production of PPE is essential for healthcare workers to respond to the pandemic; however, numerous additional measures must be taken to both, minimize the spread of the virus and facilitate a speedy recovery from the pandemic. For example, several countries have mandated people to wear masks [20], practice social

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distancing [21], and avoid unnecessary contact with "commonly touched surfaces" such as door handles to minimize transmission due to surface contact. To support the adoption of these "passive" measures, several designers have proposed additional protective solutions that leverage AM capabilities. For example, numerous designers have proposed solutions for hands-free door openers [22]; these solutions attach to door handles to prevent users from using their hands to open the doors, consequently minimizing surface contact. Similarly, François et al. [23] discuss the design of three AM solutions for minimizing surface contact: (1) hands-free door openers, (2) door hooks, and (3) button pushers.

Although these AM solutions to "passive" protective problems are innovative and useful, they are not as critical or urgent to the battle that healthcare workers are facing on the frontlines of the pandemic. For instance, the failure of a hands-free door opener will not expose the user to life-threatening situations. In comparison, failure of safety-critical PPE (e.g., face masks) with complex functional and regulatory requirements could expose healthcare workers to grave dangers. Prior research suggests that the complexity [24–27] and urgency [28,29] of problems influence the creativity of the solutions developed for them, especially in DfAM settings [30,31]. As previously discussed, many of the challenges arising from the COVID-19 pandemic are urgent and have complex functional and regulatory requirements (e.g., face masks) compared with other challenges related to the pandemic that have less urgent and relatively simpler requirements (e.g., hands-free door openers). This difference in the urgency and complexity of problems could influence the characteristics of the solutions developed for the problem. *Unfortunately, little research has explored the effects of problem definition—specifically complexity and urgency—on the characteristics of AM solutions, especially in rapid response situations, and our aim in this research is to explore this research gap.* Toward this aim, we seek to answer the following three research questions (RQs):

(1) *RQ1: Does DfAM utilization in AM solutions vary based on the problem definition and if so, how?*
(2) *RQ2: Does the manufacturability of AM solutions vary based on the problem definition and if so, how?*
(3) *RQ3: Does the creativity of AM solutions vary based on the problem definition and if so, how?*

We hypothesize that problems defined with urgent and complex requirements (e.g., face masks) will lead to the generation of solutions with higher DfAM utilization and creativity compared with problems defined with simpler and less urgent requirements (e.g., door openers). This hypothesis is based on prior work (e.g., see Refs. [24,26,27,30]) suggesting that designers presented with problems of moderate to high complexity—comprising explicit objectives and constraints—generated solutions that were more creative and better met the requirements of the problem. Furthermore, this hypothesis is informed by prior work (e.g., see Refs. [28,31]) suggesting the role of external motivation and problem urgency in encouraging the generation of creative solutions. Through the outcomes of our research, we aim to inform designers on the factors that they must focus on when developing AM solutions for rapid response problems. The approach for testing these hypotheses is introduced next.

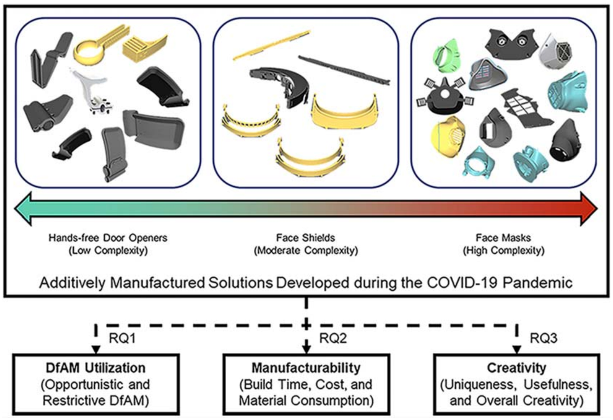

Fig. 1 Overview of our research objective in this paper

2 Experimental Methods

To answer the RQs presented in Sec. 1, we collected STL files for engineered AM solutions developed for the COVID-19 pandemic. These designs were evaluated for their DfAM utilization, manufacturability, and creativity. We discuss the details of our data collection process and the measures used for assessing the designs next.

2.1 Data Collection. A total of 26 AM solutions developed for the COVID-19 pandemic were investigated in this study. The designs were retrieved from open-source repositories such as GrabCAD,[2] Thingiverse,[3] and the NIH 3D Print Exchange.[4] The designs fell broadly into three categories: (1) hands-free door openers ($N = 8$), (2) face shields ($N = 6$), and (3) face masks ($N = 12$). These categories were chosen given the variation in the problem requirements for which the solutions were developed (see Fig. 1). In particular, hands-free door openers represented a problem defined with low complexity and urgency, face shields represented a problem defined with moderate complexity and urgency, and face masks represented a problem defined with high complexity and urgency. The complexity of the problems was defined by the number and criticality of the requirements involved. For example, as discussed in Sec. 1, face mask designs must be rigorously evaluated for aspects such as porosity and fit before they can be used by healthcare workers, and therefore, represent a complex and urgent problem definition. On the other hand, hands-free door openers have fewer and less critical requirements (i.e., enabling the hands-free opening of doors) and therefore, represent a simple and less urgent problem definition. The design repository used in this study is made publicly available at Ref. [32] and specific details about the identification of the various solutions are discussed in Ref. [32]. The designs collected were assessed for their DfAM utilization, manufacturability, and creativity using the measures discussed in Sec. 2.2.

2.2 Design Evaluation. The 26 AM design solutions collected were assessed for their DfAM utilization, manufacturability, and creativity using the metrics discussed next.

2.2.1 DfAM Utilization. To leverage the potential of AM, designers must utilize design techniques that both capitalize on AM capabilities DfAM and accommodate AM limitations [33]. Toward this end, designers must utilize opportunistic DfAM techniques (e.g., part consolidation and mass customization) to improve design functionality, while implementing restrictive DfAM guidelines (e.g., support material minimization and material anisotropy) to minimize build failure. DfAM utilization in the designs was assessed using two measures. First, all designs were assessed for their AM suitability using the DfAM Worksheet developed by Booth et al. [34]. Using the DfAM Worksheet, designers can evaluate the AM suitability of designs on eight components: (1) complexity, (2) functionality, (3) support material removal, (4) unsupported features, (5) thin features, (6) stress concentration, (7) tolerances, and (8) the need for geometric exactness. Since this worksheet was developed to help designers minimize build failure, a majority of these components emphasize the limitations

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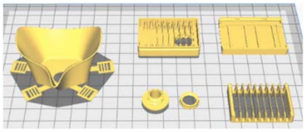
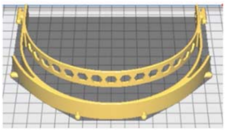
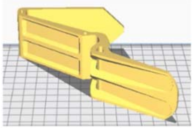
[2] https://grabcad.com/
[3] https://www.thingiverse.com/
[4] https://3dprint.nih.gov/

Table 1 Examples of solutions with corresponding DfAM utilization and creativity scores

				
		JPL Comfort single port face mask	RC2 Headband face shield	Apriporta door opener
DfAM utilization metric [37]	Part complexity	3	3	2
	Assembly complexity	3	2	1
	Number of separate parts (#)	6	1	1
	Part orientation	3	3	3
	Assembly feature orientation	3	1	3
	Smallest feature size (mm)	25.91	7.06	3
	Smallest tolerance (mm)	4.11	0	12.75
	Support material mass (g)	8	0	1
	Support material removal	2	3	2
	Largest build plate contact (mm^2)	5969.00	1221.17	1672.00
DfAM worksheet metric [34]	Complexity	1	1	3
	Functionality	2	2	2
	Material removal	3	2	1
	Unsupported features	3	2	2
	Thin features	5	3	5
	Stress concentration	3	1	3
	Tolerance	3	1	1
	Geometric exactness	5	1	3
	Total	25	13	20
Creativity metric	CAT Uniqueness[a]	4.33	2.33	5.33
	Decision Tree Originality[b]	10	5	7.5
	Novelty[c]	0.83	0.5	0.88
	CAT Usefulness[a]	4.83	3.5	3.33
	Quality[d]	2	2	2
	CAT Overall Creativity[a]	5	3.83	4.5

[a] Ref. [38].
[b] Ref. [39].
[c] Ref. [40].
[d] Ref. [41].

of AM processes, except for (geometric) complexity. However, researchers (e.g., Seepersad et al. [33] and Simpson et al. [35]) have suggested that to fully leverage the potential of AM processes, designers must account for both, the capabilities of AM—through opportunistic DfAM—and the limitations of AM—through restrictive DfAM. Consequently, designers must transition from a limitation-based design for manufacturing approach toward a "dual" DfAM mindset [36]. Therefore, in addition to the DfAM worksheet, the designs were evaluated using the ten metrics proposed by Prabhu et al. [37] that emphasize both, opportunistic and restrictive DfAM. Specifically, the designs were evaluated for (1) part complexity, (2) assembly complexity, (3) number of components, (4) part build orientation, (5) assembly feature orientation, (6) smallest feature size, (7) smallest tolerance, (8) support material, (9) ease of support removal, and (10) build plate contact area. We provide examples of DfAM utilization scores in Table 1.

2.2.2 *Manufacturability.* The manufacturability of the solutions was assessed based on three criteria: (1) build time, (2) build cost, and (3) build material. This data was simulated using Ultimaker Cura[5] and the build parameters used for simulating the manufacturability of the designs are presented in Table 2. The manufacturability data generated is also made publicly available along with the designs at Ref. [32]. It should be noted that the manufacturability data simulated for the complete build (i.e., including support structures and brims) was used in this study. Additionally, it should be noted that while we only used the data corresponding to Polylactic Acid (PLA) material and 50% infill density in this paper, the dataset at Ref. [32] consists of data for additional materials (e.g., nylon and acrylonitrile butadiene styrene) and infill densities (e.g., 20% and 100%).

2.2.3 *Creativity.* The creativity of the AM solutions in our investigation was assessed on three criteria: (1) uniqueness, (2) usefulness, and (3) overall creativity. These three criteria were chosen based on prior work (e.g., see Refs. [42–45]) arguing for the assessment of creativity of solutions as a composite of their novelty (e.g.,

Table 2 Print parameters used for simulating manufacturability data

Parameter	Value
Filament material (primary and support)	PLA (cost: $0.2/m)
Infill	50%
Layer height	0.2 mm
Wall thickness	0.8 mm
Wall line count	2
Infill pattern	Triangles
Printing temperature	250 °C
Build plate temperature	85 °C
Print speed	60 mm/s
Retraction	Enabled
Z Hop when retracted	Enabled
Cooling fan speed	2%
Support overhang angle	60 deg
Build plate adhesion type	Brim

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[5] https://ultimaker.com/software/ultimaker-cura

surprising and unique) and quality (e.g., appropriate and useful). Multiple techniques were used to assess the uniqueness and usefulness of solutions to assess multi-method convergence of the components. The specific measures used to assess these three criteria follow. We provide examples of creativity scores in Table 1.

2.2.3.1 Uniqueness.

The uniqueness of the solutions was assessed using three techniques. First, uniqueness was assessed using the Consensual Assessment Technique (CAT) proposed by Hennessey et al. [46] and Amabile [46,47]. Raters were asked to score each design on a scale of "1 = low uniqueness" to "6 = high uniqueness." Moreover, raters were asked to compare uniqueness relative to other ideas in the sample (e.g., face masks were scored relative to other face masks in the sample), as suggested in Ref. [47]. All designs were rated by three raters, and an overall intraclass correlation coefficient (ICC) [48] >0.7 was observed between the CAT scores. An average of the scores from the three raters was used as the representative score for each design [46]. Second, the novelty of the ideas was evaluated using the infrequency-based categorization technique proposed by Jansson and Smith [40]. Three raters classified ideas based on the similarity between the ideas. Any disagreements between the classifications provided by the raters were easily resolved through discussions, and a novelty score for each design was calculated using Eq. (1)

$$Novelty = 1 - \frac{Number\ of\ similar\ \ ideas}{Total\ number\ of\ ideas} \tag{1}$$

Finally, the originality of the ideas was evaluated using the decision tree proposed by Kershaw et al. [39]. Three raters scored the ideas using the 10-point scale and the reliability of the originality scores was established through an observed ICC > 0.7.

It should be noted that multiple measures of uniqueness were used in our study in light of prior research suggesting the lack of agreement between objective and subjective measures of uniqueness [49], especially in studies related to DfAM [50]. Using multiple measures would help identify any potential differences in effects due to the choice of measure and also work toward triangulating our findings. Furthermore, while the measures of uniqueness (CAT) and novelty were used to measure local uniqueness (i.e., within the studied sample) [47], originality was used to measure global uniqueness (i.e., compared with other solutions for the given problem).

2.2.3.2 Usefulness.

The usefulness of each AM solution was evaluated using two measures. First, three raters evaluated the usefulness of the designs using the CAT. Raters were asked to score each design on a scale of "1 = low usefulness" to "6 = high usefulness." They were asked to subjectively score how well each design met the requirements of the problem for which it was developed. The reliability of the scores was established through an overall observed ICC > 0.7 for the CAT scores, and an average of the three scores was calculated for each design. Second, the quality of the designs was assessed using the three-point scale proposed by Linsey et al. [41]. Three raters evaluated all the designs, and the evaluations were compared with resolve any disagreements. The scores provided by the rater with the most prior experience in DfAM and creativity-related research (as opposed to the mean of the scores from the three raters) were used to ensure that the scores were measured on the original 3-point scale.

2.2.3.3 Overall creativity.

The overall creativity of each AM solution was measured using the CAT and was derived from previous studies (e.g., see Refs. [30,51]). Similar to the uniqueness and usefulness assessments, three raters were asked to evaluate the overall creativity of the designs. Specifically, the raters were asked to evaluate the designs using a subjective composite mental model of uniqueness, usefulness, and any other factors not considered. The raters were asked to score each design on a scale of "1 = low overall creativity" to "6 = high overall creativity." This measure was used to evaluate the solutions over and above uniqueness and usefulness to capture any characteristics of the solutions that could contribute to the creativity of the solutions and might have been missed in the other measures (i.e., uniqueness and usefulness). The reliability of the scores was established through an overall ICC > 0.7 for the CAT scores, and an average score was calculated for each design.

3 Data Analysis, Results, and Discussions

The data collected were analyzed using statistical methods to answer the three research questions presented in Sec. 1. It should be noted that due to the small sample size and the difference in sample sizes, nonparametric tests were used for the analyses. The procedures followed for the analysis, the corresponding results, and the implications of these results are discussed in the remainder of this section.

3.1 RQ1: Does DfAM utilization in Additive Manufacturing Solutions Vary based on the Problem Definition and if so, How?. To answer the first research question, Kruskal–Wallis H tests [52] were performed with the problem definition as the independent variable and the DfAM utilization scores as the dependent variable. From the results of the analysis, summarized in Table 3, we see a significant effect of the problem definition on the DfAM utilization in the solutions. Specifically, we see that face masks (i.e., high complexity and urgency problem) scored the lowest on AM suitability as assessed using the DfAM Worksheet. On the other hand, hands-free door openers (i.e., low complexity and urgency problem) scored highest on AM suitability. This finding is problematic as the lower AM suitability of the designs could result in higher build failures [34], thereby hampering the rapid response for which these solutions were developed. More worrisome is the finding that solutions for more complex and urgent problems are less suitable for AM and therefore, more likely to fail than simple and less urgent problem solutions. Ideally, it would be the other way around; therefore, *if designers intend to leverage the rapid manufacturing capabilities of AM processes to respond to urgent and critical problems, then they must sufficiently emphasize the AM suitability of their solutions to minimize build failure.* Such emphasis on AM suitability can help designers

Table 3 Comparing DfAM utilization in the AM solutions between the three problem definitions

			Mean rank		
DfAM integration metric	Test statistic	p	Door openers	Face shields	Face masks
DfAM worksheet score	11.20	<0.01[a]	*7.00*	**12.17**	***18.50***
Part complexity	1.42	0.49	11.19	14.83	14.38
Assembly complexity	3.55	0.17	14.06	9.00	15.38
Number of parts	10.71	<0.01[a]	**11.88**	*6.50*	***18.08***
Part orientation	6.14	<0.05[a]	*9.75*	***16.00***	**14.75**
Assembly feature orientation	11.49	<0.01[a]	**10.69**	*8.00*	***18.13***
Smallest feature size	3.81	0.15	17.81	12.33	11.21
Tolerance	6.63	0.04[a]	*8.50*	**14.75**	***16.21***
Support material mass	7.13	0.03[a]	*8.38*	**12.50**	***17.42***
Support material removal	4.14	0.13	17.44	13.58	10.83
Build plate contact area	4.71	0.10	9.25	12.67	16.75

Note: Lowest value is in italics, moderate value is in bold, and highest value is in bold italics.

[a] $p < 0.05$.

ensure that their solutions can be feasibly deployed and therefore, provide an effective rapid response to these problems.

The second important result is that the DfAM utilization in the solutions varied based on the problem definition. Specifically, we observe that face mask designs tend to comprise more components, which suggests that face mask designs do not sufficiently leverage part consolidation to minimize build and assembly time and costs. Kursat Celik et al. [7] demonstrate the value of part consolidation to reduce build time when designing face shields. Therefore, if designers intend to design face masks that can be rapidly produced, they should emphasize part consolidation to reduce part count and minimize the need for assembly. Furthermore, we observe that face mask designs also incorporate more appropriate tolerances compared with face shields and door openers. *This is a positive observation as it suggests that despite consisting of more components, face masks are potentially easier to assemble and therefore, are less likely to fail during assembly*.

Moreover, we observe that face masks required more support material compared with face shields and hands-free door openers. Prior research has demonstrated that support material positively relates to overall build material and build time. Therefore, designers must also aim to minimize support material through techniques such as self-supporting angles and bridging limits. *This emphasis on minimizing support material can help facilitate the development of designs that print fast and consume low material, which could, in turn, facilitate a rapid response to the shortage of face masks through DfAM*.

3.2 RQ2: Does the Manufacturability of Additive Manufacturing Solutions Vary based on the Problem Definition and if so, how?. To answer the second research question, Kruskal–Wallis H tests [52] were performed with the problem definition as the independent variable and the manufacturability criteria (i.e., build time, cost, and material) as the dependent variables. From the results (See Table 4), we see that face shields demonstrated the lowest build cost and build material. Moreover, we see that hands-free door openers and face masks demonstrated similar build costs and material usage. Finally, we see a similar trend in the build time of the designs; face shields demonstrated lower build times compared with face masks and hands-free door openers; however, the differences in build time were not statistically significant. These results suggest that although the shortage of face masks is the most critical and urgent challenge, solutions developed for this problem might not be sufficient for rapid response. These results further reinforce our previous inference that face mask designs do not sufficiently emphasize DfAM techniques such as part consolidation and minimization of support material. *Designers must, therefore, emphasize DfAM—both opportunistic and restrictive—to improve the manufacturability of designs, especially when responding to critical and urgent requirements such as the shortage of PPE*. However, we must be careful in making these inferences as the differences in the manufacturability could also be attributed to potential differences in the size of the solutions.

Table 4 Comparing manufacturability of the solutions between the three problem definitions

			Mean rank		
DfAM integration metric	Test statistic	p	Door openers	Face shields	Face masks
Build time	2.65	0.27	14.00	9.17	15.33
Build cost	5.19	0.08[a]	**14.63**	*7.33*	**15.83**
Build material	5.19	0.07[a]	**14.63**	*7.33*	**15.83**

Note: Lowest value is in italics, moderate value is in bold.
[a] $p < 0.1$.

3.3 RQ3: Does the Creativity of Additive Manufacturing Solutions Vary based on the Problem Definition and if so, How?. To answer the third research question, we performed Kruskal–Wallis H tests [52] with the creativity scores as the dependent variable and the problem definition as the independent variable. From the results (see Table 5), we see that the problem definition only influenced the quality of the designs as assessed using Linsey et al.’s three-point scale. Specifically, we see that designs for hands-free door openers scored lowest on quality, whereas face shields scored the highest. No differences were observed in other creativity measures. These results refute our stated hypothesis that solutions generated for problems of high complexity and urgency would demonstrate higher creativity. Moreover, this result suggests that when designing for AM for problems and challenges related to the COVID-19 pandemic, designers generate solutions of similar creativity, irrespective of the urgency of the problem at hand. The lack of differences in the creativity of the solutions presents the opportunity to leverage frameworks such as the one proposed by Fiorineschi et al. [53] to support the systematic and creative exploration of the design space in time-critical design challenges.

4 Concluding Remarks, Limitations, and Directions for Future Work

Additive manufacturing offers designers the capability to realize a rapid response to challenges imposed by the COVID-19 pandemic. To leverage this offering, designers must generate solutions that are creative *and* can be feasibly manufactured using AM. Prior research suggests that problem definition (e.g., urgency and complexity) influences the creativity of solutions designed for the problem. However, little research has investigated the influence of problem definition on the characteristics of AM solutions, especially in rapid response challenges, and our aim in this study is to investigate this research gap. Toward this end, we compared DfAM utilization, manufacturability, and creativity of open-source (1) hands-free door openers (problem with low complexity and urgency), (2) face shields (problem with moderate complexity and urgency), and (3) face masks (problem with high complexity and urgency).

Our first key finding was that problem definitions negatively related to the AM suitability of the solution, i.e., face masks demonstrated the lowest AM suitability, whereas hands-free door openers demonstrated the highest AM suitability. This low AM suitability of solutions is detrimental to the effectiveness of rapid response as this implies that solutions for more complex and urgent problems are more likely to suffer a build failure. Moreover,

Table 5 Comparing creativity of solutions between the three problem definitions

				Mean rank		
Creativity component	Creativity metric	Test statistic	p	Door openers	Face shields	Face masks
Uniqueness	Uniqueness[a]	0.47	0.79	13.25	15.33	12.75
	Originality[b]	2.52	0.28	10.25	15.92	14.46
	Novelty[c]	3.93	0.14	10.50	11.33	16.58
Usefulness	Usefulness[a]	2.14	0.34	16.75	12.50	11.83
	Quality[d]	14.20	<0.001[e]	*6.63*	***18.00***	**15.83**
Overall Creativity[a]		2.03	0.36	13.88	16.92	11.54

Note: Lowest value is in italics, and highest value is in bold italics.
[a] Consensual Assessment [38,46,47].
[b] Decision Tree [39].
[c] Ref. [40].
[d] Ref. [41].
[e] $p < 0.05$.

we observed that although face mask designs incorporated more appropriate tolerances, they also consumed more support material and had a higher number of parts, missing benefits that would have come from a focus on part consolidation. Second, we observed that face shields demonstrated the highest manufacturability, i.e., lowest build time, cost, and material, compared with face masks and hands-free door openers. This observation implies that solutions for complex and urgent problems are not necessarily the most efficient to manufacture, thereby reinforcing the need to utilize DfAM techniques to improve the manufacturability of rapid response AM solutions. Our final key finding was that the problem definition did not relate to the creativity of the solutions, which refuted one of our main hypotheses. Designs from all three categories, i.e., face masks, face shields, and hands-free door openers, had similar distributions of creativity scores. These findings suggest that when designers are developing AM solutions for urgent and complex problems, they must give sufficient emphasis to the AM suitability and manufacturability of their solutions as well as being creative in how they address the problem requirements. This emphasis on AM suitability and manufacturability can be achieved by appropriately evaluating designs for their DfAM utilization.

The findings of our research provide important insights into the role of problem definitions in DfAM tasks; however, our study has several limitations. First, we only evaluated solutions developed for a single problem within each category. Future work must extend the findings of our research to study solutions for multiple problems within each category of complexity and urgency. Such an investigation will test the generalizability of our findings across different design problems. The second limitation is that the solutions for the problems chosen for our study could have varied in their typical sizes. Although the three problems were picked such that the solutions were relatively similar in size, variations in the sizes of solutions could have influenced size-based measures such as build material and largest build plate contact. Therefore, future work must aim to replicate our findings using similar-sized designs—or normalizing manufacturability results within each solution category. Furthermore, as the pandemic continues to unfold, several new solutions are rapidly being developed for these solutions, as well as numerous other problems related to the pandemic. Therefore, future work must extend these findings with an updated set of solutions obtained from a broader search from repositories such as GitHub.[6] Third, we only evaluated the current version of the solutions in our research. As discussed by Kursat Celik et al. [7], these solutions often develop over time through numerous design-prototype-test cycles. Moreover, these solutions could have been built with AM to test the feasibility and viability of the designs [54] with the intent of shifting toward mass production using other manufacturing techniques such as injection molding. Therefore, future research must study the evolution of these designs both, from a prototyping and DfAM utilization lens. Such an investigation is particularly important because prior research (e.g., see Ref. [55]) suggests that incubation can support creativity in engineering design. Therefore, as designs evolve over time, they could have become more creative and AM-suitable, warranting the exploration of the evolution of these solutions over time.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The data and information that support the findings of this article are freely available at: https://doi.org/10.1016/j.dib.2021.107012. The authors attest that all data for this study are included in the paper.

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