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EFFECT OF ENGINEERING DESIGN ON MITIGATION OF PLA FILAMENT WASTE TO MAKE THE PFF2 FILTER ADAPTERS FASTER FOR REUSABLE MODIFIED HALF-FACE MASK AS PPE AGAINST THE COVID-19 VIRUS BY THE FDM ADDITIVE MANUFACTURING

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Abstract. *The present work reports the results of a study on how to mitigate filament waste and reduce printing time through a systematic investigation and improvement of the effective engineering design to optimize the FDM additive manufacturing process. Aiming to attain the target in short time, a commercial reusable half-face mask with one valve was used as a base to develop as a PPE - Personal Protection Equipment for use hospital with two kinds of PFF2 filter adapters. The PFF2 filters adapters were designed using a free licensed CAD software. The printing of PFF2 adapters was conducted using biodegradable PLA thermoplastic filament through the material extrusion process. The FDM printer employed was a low cost commercial printer used for hobby. As a result, a total of five different parts were designed and printed to prepare three sets of PFF2 filter adapters to get a half-face mask as a targeted mask as PPE. Considered two main parts of adapters, first designed parts required printing of supports to the main part to be printed, resulting increase of printing time, waste of filament and increase of final cost of mask adapters. With design improvement, considerable mitigation of waste of filament and time were attained.*

Keywords: *Reusable Modified Half-Face Mask, Adapter for PFF2 Filter, PLA, FDM 3D Printing Process, CAD Design, Design Optimization, covid-19, Brasmasc Project*

1. INTRODUCTION

The COVID-19 pandemic decreed by the WHO - World Health Organization in March 2020, caused by the new SARS-CoV-2 coronavirus has caused major behavioral changes in society, especially regarding the use of personal protective equipment - PPE, especially face masks, due to its high transmissibility and lethality. However, the scarcity of surgical masks and N95/PFF2 in the global market has led to cloth masks being adopted by the general population, despite their limited effectiveness. The emergence of virus variants with greater transmission power has resulted in the requirement for the use of PFF1 and PFF2 masks in countries such as Germany and France. The use of these masks, mostly disposable, results in increasing financial cost and waste generation, especially for those forced to expose themselves frequently to the new coronavirus, and the lack of a complete seal in this type of PPE limits the protection offered and does not completely reduce transmissibility. Moreover, although the spread of vaccines gradually reduces the need for PPE, the emergence of new variants still presents a great risk, especially to healthcare workers forced to expose themselves frequently. The "Swiss cheese" model shown in Figure 1, advocated by Australian virologist Dr. Ian

M. Mackay (NY Times, 2020), combining layers of protection to compensate for the fact that no preventative measure is completely effective, still recommends masks, especially for those forced to expose themselves frequently.

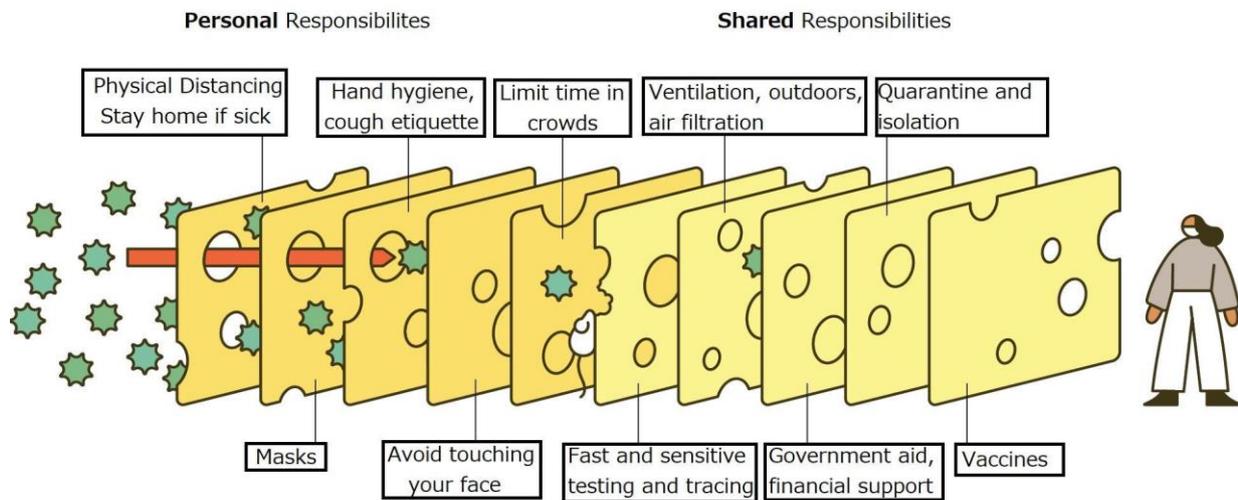


Figure 1. Swiss cheese layers model for a better protection against COVID-19 (NY Times, 2020).

An alternative to disposable masks, more interesting for both personal and collective safety, is the utilization of commercial reusable respirators adapted for use in the environment of the COVID-19 pandemic, offering better sealing for inlet and outlet air, provided that they do not have exhalation valves, adapted for use with PFF2/N95 filters. One problem with these reusable respirators is the high cost of their filters, often higher than the cost of disposable masks. Thus, due to the scarcity of masks of adequate quality on the market, especially for healthcare professionals who are potentially exposed to the virus, there is a need to urgently, due to the ongoing pandemic with new variants, manufacture safer masks to help reduce the infection rate, especially in hospitals. The solution adopted in the larger collaborative project is to design adapters for reusable masks found in the Brazilian market, thus enabling the use of lower cost PFF2 filters, developed and manufactured in the country.

The adapters were manufactured by the 3D printing through the material extrusion process, detailed in (Calignano *et al.*, 2017), using a Fused Deposition Modelling (FDM) printer, which from a 3D model generated in a CAD software, creates the instructions for the printer, printing layer by layer, from the base to the top of the piece, using recyclable plastic filament. Since the printer itself uses FDM technology, the material extrusion process will be referred to as such in this work, as the former terminology is more widespread and the Stratasys patent expired. This method offers great advantages for the development phase of the project, as no adaptations of the equipment are required for each modification of the model, allowing for successive iterations. Nevertheless, the material extrusion process suffers from some limitations, mainly in printing time, which in some cases can exceed 24 hours. Moreover, during development, a major limitation of the process became clear, detailed in (Hubs, 2020): if the piece contains overhanging parts, supports will be printed, which must be removed after manufacturing. The existence of these supports results in material waste, which reached 48% in one of the prototypes, besides increasing the printing time. Hällgren (2016) detailed a study on redesigning parts for different additive manufacture methods, exploring the trade-off between cost, mass, printing time and performance. The present work focuses on reducing or eliminating the waste through modifications in the design of the adapters, eliminating the need for the supports, in order to make the printing faster and cheaper, thus reducing its cost, considered the most important factor.

Furthermore, in order to relate the needs of users with the technical requirements of the product, the QFD (Quality Function Deployment) was used in this work, a methodology that guided the decision-making for the design of the half-facial protective mask against COVID-19. In Bueno and Toledo (2017) a review of the use of techniques and methodologies is presented, indicating the mechanisms Stage-gates, QFD, APQP, FMEA as relevant for product development process. Luiz (2019) cites that QFD (Quality Function Deployment) relates variables and analyzes the degree of relevance among them in order to facilitate decision making by the designers. QFD can be applied to various types of products, Gain (2020) uses the tool to understand the user requirements of a food delivery system during the covid-19 scenario. During the application of the method, matrices are built according to the QFD phases that relate and quantify parameters, indicating the relevance of each one in the face of the requirements demanded by the users. In the

present work, only the first QFD matrix was built, since the interest lies in the initial specification of the product in order to guide the design of the semifacial mask components taking into account the vision of the likely customers.

2. MATERIALS AND METHODS

2.1 Design and FDM 3D Printer.

The Brasmasc Semifacial project consists of three adapters, two lateral and one central, all equipped with commercial PFF2 filters. For the development of the adapters, the license-free CAD software DesignSpark was used, chosen due to the familiarity of the authors with it, especially given the speed required in the development. Through this CAD software, the geometry was elaborated taking into account the requirements of the filter, mask and seal, generating at the end a file in .STL format.

The printer used was the Ender 5, from the Chinese manufacturer Creality, that works through the material extrusion process, using biodegradable thermoplastic polylactic acid filament, or PLA, chosen due to its good availability and cost in the market. The filament diameter used was 1.75 mm, with a layer height between 0.1 and 0.2 mm. In addition, the temperature of the printing nozzle was maintained at 209°C. For generating the printing instructions from the model, Ultimaker Cura software was used, also chosen due to the familiarity of the authors, as well as the resulting good quality in printing.

From the file, the adapters were printed and tested, followed by discussions among the authors about improvements and ways to eliminate the print support and consequently the waste. After the discussions, new models were elaborated through DesignSpark and printed, where a new battery of tests and discussions were held, iterating on this process (model-print-test-discussions) until the waste was completely eliminated, as this was the main objective of this work. The improvements made in each prototype are detailed in their own sections.

2.2 Quality Function Deployment - QFD

To obtain the requirements of the users of the COVID-19 protective mask, further research with questionnaires and surveys could be conducted, as was done in Esmail (2020). Since translating the voice of the customer is not the main objective of this paper, the present work does not encompass a formal market survey of the likely consumers of the COVID-19 semifacial protective mask. A more simplified way to obtain the most relevant technical parameters was adopted, and the main customer requirements were determined by the team itself, based on non-formalized discussions with healthcare professionals, who are the target audience of the product under development.

Table 1 lists the main customer requirements with the technical parameters with the indication of each degree of importance, scored from 1 to 5, in order to guide the designer in the design of the COVID-19 semifacial protective mask, considering healthcare professionals in their workplaces as the end user of the product.

Table 1. Customer requirements, degree of importance and associated parameters for the designer.

Customer requirements	Importance	Design parameters
Price	4	Final product cost
Durability	3	Wear-resistant material
Comfort	5	Comfortable to wear and easy to breathe design
Aesthetics	2	Discreet design
Safety	5	Virus filtering, sealing, and mask fitting
Communicability	5	Voice transmission

Table 2 represents the scoring of the design parameters against the user requirements, taking into account the corresponding degree of importance. In the relationship of customer requirements and design parameters, the following weights were considered: 9 for a strong relationship, 3 for a medium relationship, and 1 for a weak relationship.

It is worth mentioning that the other matrices and the correlation between the technical parameters were not done in this work, since the QFD was used as a simplified guide for the designer. For this reason, the QFD phase performed is sufficient to assist in the initial specification in order to meet the main objectives of the product and of this work.

Table 2. Matrix of the relationship between user requirements and technical parameters with the score.

Design Parameters		Final cost	Wear resistant material	Comfortable to wear and easy to breathe design	Discreet design	Virus filtering, sealing, and mask fitting	Voice transmission
Client Requirements	Importance						
Price	4	9	3	1		3	
Durability	3	3	9			1	
Comfort	5	1		9	1	3	3
Aesthetics	2			1	9	1	3
Safety	5	3	1	3	1	9	3
Communicability	5			3	3	3	9
Criteria scoring		65	44	81	43	92	81

3. RESULTS AND DISCUSSIONS

In this section, to do as detailed as possible discussion of obtained results, two main adapters, (i) lateral and (ii) center adapters, were developed, printed and analyzed as follows.

3.1 Lateral adapter

3.1.1 Lateral adapter - First prototype

The design of the side adapter was made based on the diameter of the PFF2 filter to be used, as well as the dimensions for the bayonet-type coupling with the selected mask. A stepped design has been elaborated, with a focus on keeping the adapter relatively compact, as well as being able to be made more rapidly. In addition, a cap with an inner ring for better sealing was also designed.

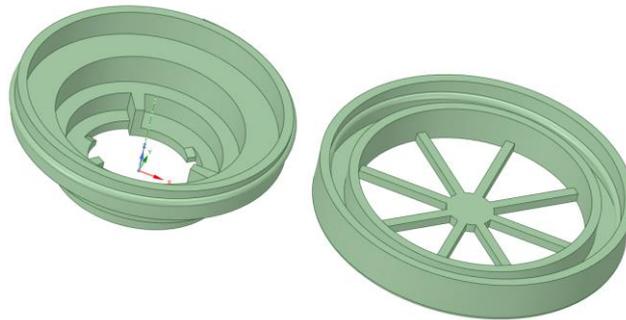


Figure 2. Lateral adapter V1 and Lid V1.

The main problems found in this first prototype were: the presence of a diaphragm effect in the filter during breathing, resulting in noise that caused discomfort; poor ergonomics resulting from the lack of support for attaching and removing the lid; and mainly the need for a large amount of support during the print, resulting in increased printing time and cost, as well as causing a waste of 5.0g of a total of 16.3g of material, i.e. 30.67% waste.

3.1.2 Lateral adapter - Second prototype

As the need for support during printing is related to the existence of overhanging regions, the second design abandoned the stepped design, adopting a design where the base is connected to the thread section with a 45 degree inclination to the vertical. This inclination could theoretically be up to 60 degrees, however simulations showed that due

to the length of the inclined area, supports would still be required. In addition to eliminating waste, this design also intended to improve the ergonomics of the adapter.

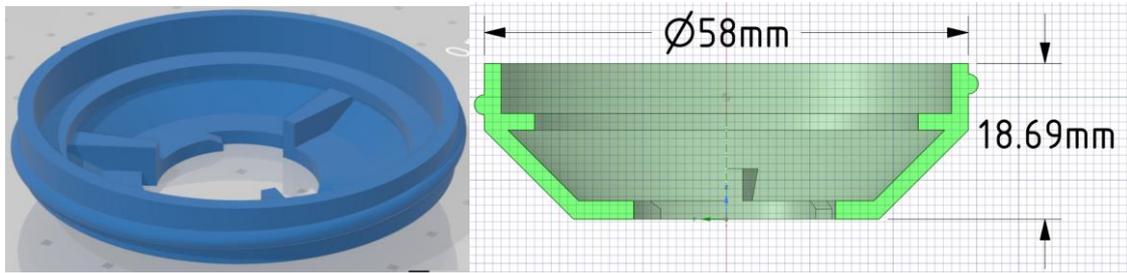


Figure 3. Lateral adapter V2.

After printing, the elimination of the bottom supports was found to be successful. Despite this, the marquee present in the filter mounting region caused the printing of internal supports, resulting in 0.3g of residue from a total of 11.2g of material, a huge improvement compared to the first prototype.



Figure 4. Internal supports in the second prototype of the lateral adapter. The photograph is in scale with the model shown in Figure 3.

3.1.3 Lateral adapter - Third prototype

The third prototype was a refinement, where the only modification was enclosing the marquee region in an attempt to completely eliminate the need for supports. After printing, it succeeded in completely eliminating the supports during printing, improving the finish and eliminating waste generation. As such, the side adapter was deemed complete, with only incremental improvements left to appear during testing.

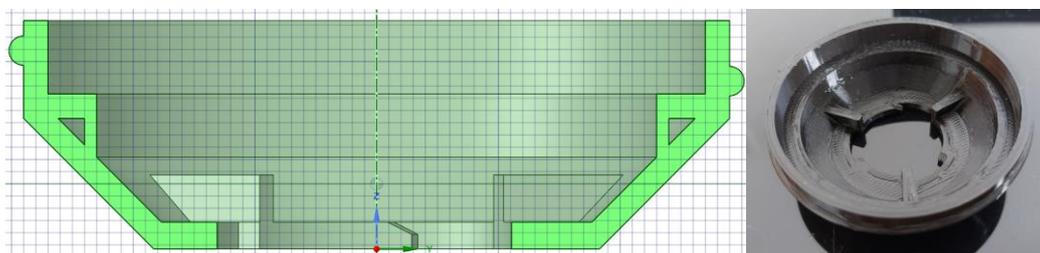


Figure 5. Lateral adapter version V3. Left scheme is design and the right is after 3D printing.

3.1.4 Lateral adapter - Results

As can be seen in Figure 6, the modifications in the adapter design made it possible to eliminate the supports during manufacturing through the FDM technology, thus generating a 30.67% material saving in printing, a factor associated with a reduction in cost and manufacturing time. In addition, the absence of the supports also resulted in an improved surface finish, making it more aesthetically pleasing.

Lateral adapter comparison

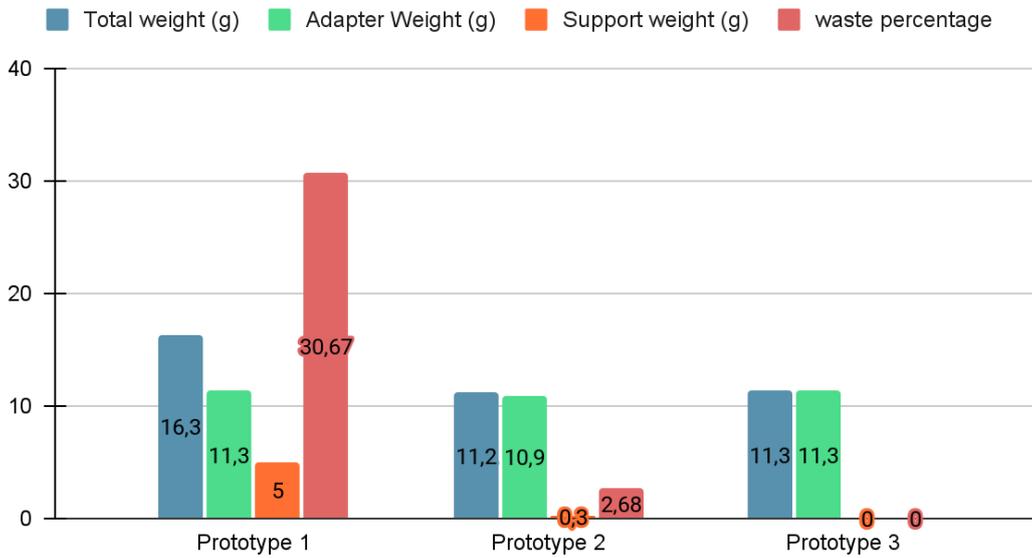


Figure 6. Comparative graphic between the different lateral adapter prototypes.

3.2 Frontal adapter

3.2.1 Frontal adapter - First prototype

The design of the frontal adapter followed the same guidelines as the lateral adapter, with the difference being its attachment to the half-facial respirator. Due to its geometry, a nut-screw type of attachment was selected, with a portion of the adapter entering the respirator orifice and being secured internally by a nut, also featuring a passage for airflow and improved communicability. In addition, a pair of O-rings, one external and one internal, was used to ensure good sealing of the assembly.

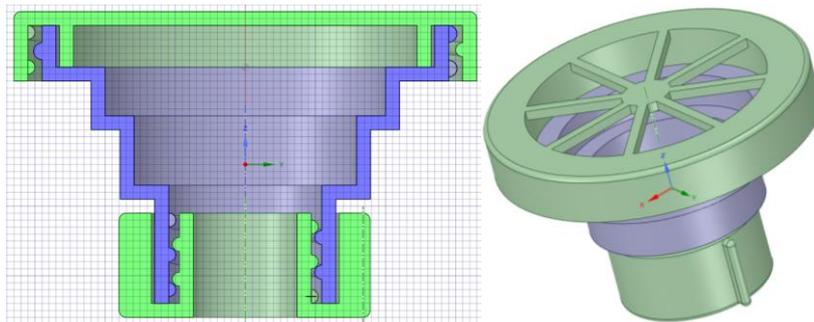


Figure 7. Frontal adapter V1.

The problems encountered in this design were similar to those encountered in the V1 side adapter, with one aggravating factor that, due to the diameter of the bottom steps being much smaller compared to the top step, a huge amount of waste was generated, 14.1g out of a total of 29.1g of printed material, representing a waste of 48.45%.

3.2.2 Frontal adapter - Second prototype

Following the considerations discussed in the section 3.1.2, we sought to eliminate the steps present in the design, however due to limitations related to the geometry of the mask and the way the adapter is attached, the step related to the internal thread could not be eliminated. Nevertheless, the elimination of the top step would already represent enormous material savings.

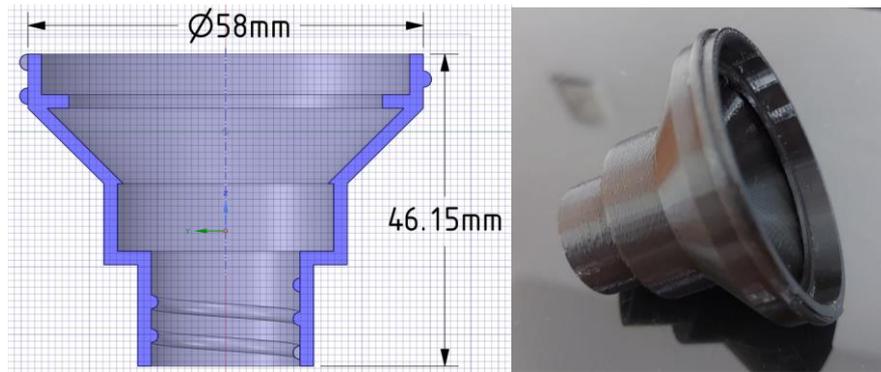


Figure 8. Frontal adapter version V2. On the left is the design of the frontal adapter and on the right is the printed piece. The photograph is in scale with the model.

After printing, the same problem was found as with the side adapter V2, where the presence of the marquee in the filter mounting region caused the printing of internal support. Also, besides the expected support at the bottom step, an external support was also needed at the inclined region, shown in Figure 9 below. The need for this support is possibly related to the height of the region in relation to the base.

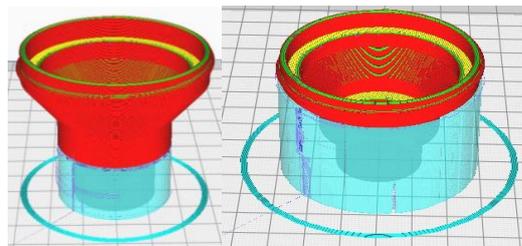


Figure 9. Frontal adapter V2 print simulation in Ultimaker Cura software, with support locations shown in light blue.

3.2.3 Frontal adapter - Third prototype

The third prototype sought only to correct the problem of the marquee, closing it in a similar way to the third prototype of the side adapter. Despite the need for support in printing, the amount of waste dropped from 14.1g to 2.7g in this prototype, a considerable improvement.

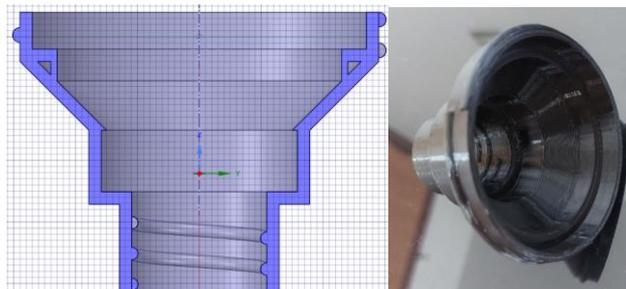


Figure 10. Frontal adapter V3.

3.2.4 Frontal adapter - Fourth prototype

Aiming to completely mitigate manufacturing waste of PLA filament, a new design was discussed and developed for setting the central adapter, whereby a hollow bolt was developed to be fixed inside the respirator, with the adapter now acting as the nut. Through this new conception, the last step could be eliminated. After printing, success was verified in completely eliminating the supports, thus eliminating manufacturing waste. In addition, the new design reduced the overall height of the adapter, also improving the aesthetics.

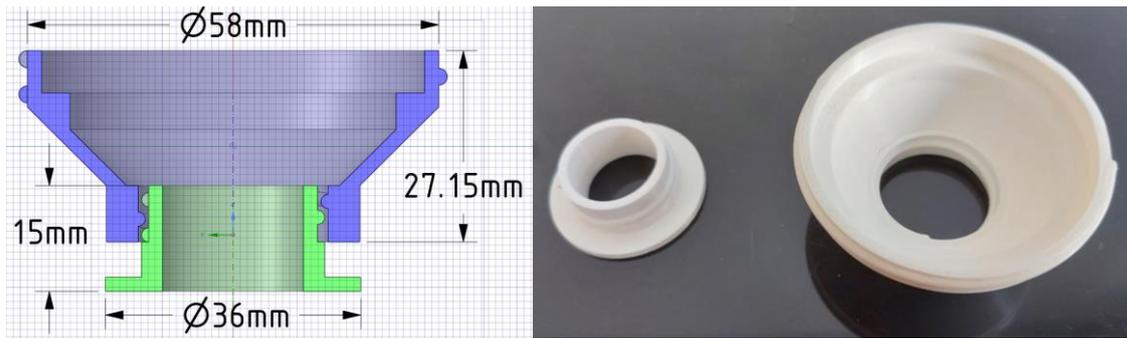


Figure 11. Frontal adapter V4. The photograph is in scale with the model.

3.2.5 Frontal adapter - Results

As shown on Figure 12, the modifications to the adapter design made it possible to eliminate the supports during fabrication using the FDM technology, thus generating a savings of 56.01% of material in the print, a factor associated with a reduction in cost and fabrication time. In addition, the absence of supports has also resulted in an improved surface finish, making it more aesthetically pleasing. Finally, the new design offers a 79% increase in airflow area when compared to the previous nut, improving airflow and communicability.

Frontal adapter comparison

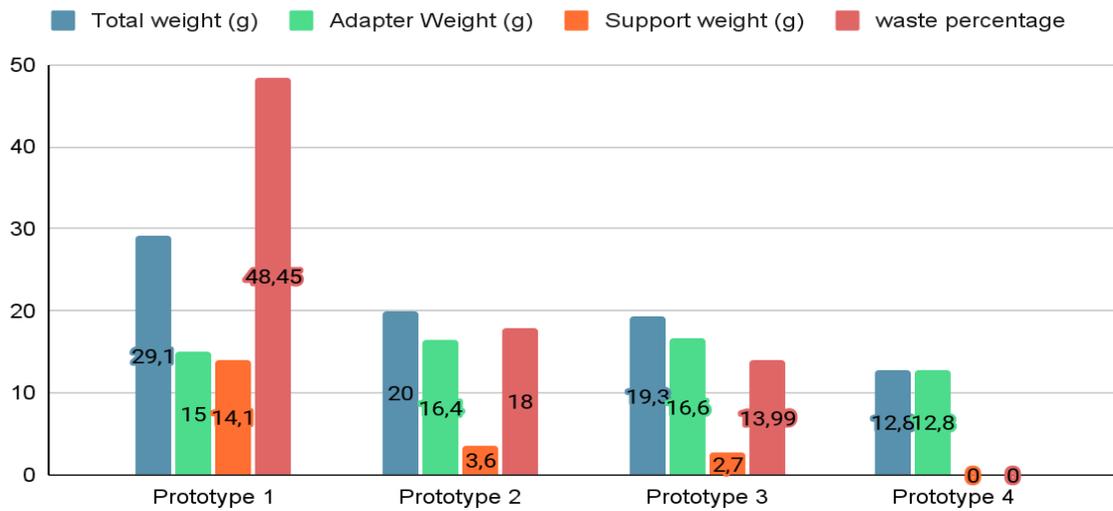


Figure 12. Comparative graphic between the different frontal adapter prototypes.

3.3 QFD comparison

Table 3 comprises a comparative analysis between the mask with the adapters discussed in this paper, shown as product A, and two other half-facial masks on the market.

Table 3. Comparison of the evaluation of each product.

Design parameters		Competitive evaluation		
Client requirement	Importance	Product A	Product X	Product Y
Price	4	8	6	9
Durability	3	9	9	9
Comfort	5	8	8	6
Aesthetics	2	5	5	5
Safety	5	10	8	7
Communicability	5	5	4	4
Criteria Scoring				
Product A scoring		184		
Product X scoring			161	
Product Y scoring				158

Figure 13 shows developed adapters for PFF2 filters mounted on a commercial half-face mask.



Figure 13. A side and frontal view of PFF2 filter adapters (in blue and black color) developed for half-Face mask as PPE by the FDM additive manufacturing process.

4. CONCLUSIONS

The FDM additive manufacturing process is an interesting manufacturing process to develop a new product from filament in a short time, even during pandemic of covid-19. Furthermore, the production engineering tool for product engineering QFD - Quality Function Deployment helped to guide the focus on several parameters required for a product, in particular reduction of production cost by mitigation of waste of filament and reducing printing time as well. In special, establishment of a research group of several different expertise members working in collaborative mode. Thus, based on the results attained, it became clear the need to adopt the product design principle to the manufacturing method used to manufacture it.

- a) For the material extrusion printing process, this adaptation consists in eliminating or reducing as much as possible the overhang regions, transforming eventual "steps" into inclined regions, keeping the inclination angle with the vertical below 45°.

- b) In some cases, it is impossible to eliminate overhang regions. In these situations, other ways to eliminate waste can be used, such as dividing a model into two or more parts, so that each part is printed without supports. These solutions should be evaluated by the designer.
- c) By modifying and improving the design of PFF2 adapters, it was possible to reduce or even totally mitigate PLA filament waste, reducing the manufacturing cost and saving FDM printing time.

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