Mass-production and Distribution of Medical Face Shields Using Additive Manufacturing and Injection Molding Process for Healthcare System Support During COVID-19 Pandemic in Brazil

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Abstract

Face shields have been adopted worldwide as personal protective equipment for healthcare professionals during the COVID-19 pandemic. This device provides a transparent facial physical barrier reducing the exposure to aerosol particles. The fused deposition modeling (FDM) is the most applied process of additive manufacturing due to its usability and low-cost. The injection molding (IM) is the fastest process for mass production. This study is the first to perform a qualitative comparison between the use of FDM and IM processes for mass production and rapid distribution of face shields in a pandemic. The design of the face shield and tests were conducted in prototyping cycles based on requirements of medical, Brazilian standards, manufacturing, and production. The FDM face shields manufacturing was carried out by a volunteer network, and the IM manufacturing was carried out by companies. The volunteers produced 35,000 medical face shields through the FDM process with daily delivery to several hospitals. A total of 80,000 face shields was produced by the IM process and delivered to remote Brazilian regions. The mass production of 115,000 face shields protected health professionals from public hospitals in all states of Brazil. In a pandemic, both FDM and IM processes are suitable for mass production of face shields. Once a committed network of volunteers is formed in strategic regions, the FDM process promotes a fast daily production. The IM process is the best option for large scale production of face shields and delivery to remote areas where access to 3D printing is reduced.

1. Introduction

Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) or Coronavirus Disease 2019 (COVID-19) is a life-threatening disease caused by a novel coronavirus that has caused a large global outbreak [1]. The transmission of this disease occurs at human-to-human level, when droplets are generated close to the eyes, nose, or mouth and reach the respiratory system or through direct contact with contaminated surface followed by the touching of the eyes, nose, or mouth [2]. The most common symptoms are fever, pneumonia, and cough, but the severe cases progress to respiratory and death [3]. The COVID-19 infection began in Wuhan, China, in December 2019, and it has rapidly spread across several other countries being declared by the World Health Organization (WHO) as a major global health concern. In February 2020, after 43,000 confirmed cases in 28 countries, COVID-19 was characterized as a pandemic, and after six months, 17,321,394 cases and 673,822 deaths were registered globally [4]. In Brazil, the number of COVID-19 cases grew fast, and currently, it is the second country with the highest number of infected individuals, with a total of 2,614,662 cases, and 91,416 deaths [5].

Brazil has a hybrid health system. Every citizen has free access to the National Health System, but a private system offers services covered out of payments and insurance plans [6]. About 80% of the Brazilian population rely exclusively on the public system, reflecting striking inequalities [7]. Public health policies and infection control measures are urgently required to limit virus spread and to consequently decrease the damage associated with the COVID-19 outbreak [2,8]. In all countries affected by the new coronavirus, the increased number of cases is associated with an overwhelmed health system, resulting in shortages of personal protective equipment (PPE) such as gloves, face masks, goggles, face shields, N95 masks, and gowns [9-10]. Healthcare workers are at the front line of the COVID-19 outbreak, s they are submitted to hazards that put them at risk of high pathogen exposure [11]. To reduce the infection risk among workers, minimum contact with spread respiratory secretions through the use of PPE is essential.

Worldwide, there is no systematic and standardized reliable data regarding the number of healthcare workers that were infected or have died due to COVID-19. In March 2020, the WHO recognized that 23,000 healthcare workers were infected, probably due to lacking PPE in hospitals [11]. The International Council of Nurses (ICN) estimated that at least 230,000 healthcare workers have been COVID-19 infected and more than 600 nurses died around the world [12]. In Brazil, until the beginning of July 2020, about 83,100 doctors, nurses, biomedical, dentists, technicians, and others were diagnosed with COVID-19, resulting in 316 nurses dead [13]. Hospitals with no adequate supply of face masks suffer the dilemma of extended use, reuse, and reprocessing of their existing supply [14]. Due to PPE shortage, the Centers for Disease Control and Prevention (CDC) recommends that during the crisis, N95 respirator masks should be used only during aerosol- generating procedures, although this implies increased exposure to COVID-19 [15]. In cases of fully depleted stocks, CDC also recommends reusing masks intended for one-time use [16].

The use of barriers that block respiratory droplets seems to prevent COVID-19 transmission, among which face masks and shields are the two primary options [17]. Face shields are used for the protection of the facial area and associated mucous membranes (eyes, nose, mouth) from splashes, sprays, and body fluid spatter [18-19]. Face shields significantly reduce the amount of inhalation of the influenza virus, providing a transparent physical barrier that covers the face and can be used as adjunctive PPE, in conjunction with face masks and goggles [14,20-21]. For optimal protection, the shield should cover the forehead, extend below the chin, and wrap around the side of the face, and there should be no exposed gap between the forehead and the shield frame [17,19]. Non-use of face shields by nurses during high-risk aerosolizing procedures on patients with respiratory infections resulted in an increased risk of infection greater than three-folds. Face shields are efficient in reducing the viral exposure by 97% on a contaminated surface, but the benefits of face shields on infected persons on a sneeze or cough have not been accessed in clinical studies [22].

On 23 March 2020, the Brazilian Health Surveillance Agency (ANVISA) simplified the PPE product regulation process during the COVID-19 pandemic. Among the PPE products, the requirements for face shields production were simplified, enabling the development of alternative models [23]. Some solutions have been created using different manufacturing methods such as the ones using additive manufacturing, popularly known for 3D printing [24]. This technology allows the manufacture of physical models through the addition of materials in layers in a cost-effective and fast approach based on computer aided design (CAD). Fused Deposition Modelling (FDM) is the most accessible 3D printing process for product development due to its usability, availability of low- cost 3D printers, and the convenience of a broad range of thermoplastic material [25-29]. FDM process has been used to produce face shields using open-access models to supply the demand of hospital in the COVID-19 pandemic [30-33]. The Injection Molding (IM) is another manufacturing process that transforms raw thermoplastic material into designed parts of a particular shape. It is common and fast process for mass production of identical items through the melting and injection of plastic at high pressure into a mold designed to be the inverse of the desired part shape. [34].

Some studies indicate that the production of medical face shields can be accomplished through two manufacturing processes: FDM and IM [35-36]. However, which of the methods is the most suitable for mass production and rapid distribution of face shields in a pandemic situation? This study is the first one to compare these processes through the production of 115,000 units that were donated and distributed to support the healthcare system during the COVID-19 pandemic in Brazil.

2. Methodology

The Higia project was conceived by a group of 3D printing experts in collaboration with the medical staff from São Paulo Hospital at the Federal University of São Paulo in Brazil (HSP/UNIFESP) to support public hospitals with face shields during the COVID-19 pandemic. The name “Higia” refers to the Greek goddess who represents health, cleanliness, sanity, and disease prevention. The face shield manufacturing using the FDM process was carried out by a network of volunteers, and the manufacture using the IM process was carried out by partner companies.

2.1 Design and prototyping cycles of the Higia face shield

The process of the Higia face shield design, testing, and improvement was developed in nine days, in five prototyping cycles inspired by the open-source model Prusa RC1 [37] (Fig. 1). The Prusa RC1 model is registered under a creative commons license that allows the model to be shared and adapted for non-commercial purpose. The face shield consists of a frame, produced by 3D- printing FDM in a polymeric material, a visor (transparent plastic sheet), and a rubber band. Despite its functionality, the Prusa RC1 face shield model required longer 3D-printing time (± five hours) and the use of a more considerable amount of material. Besides, some features of the Prusa RC1 model were improved to increase the effectiveness of this device in the hospital environment based on a list of requirements and constraints that was created considering medical needs, 3D printing, ANVISA standards, and production logistics (Fig. 2).

The frame of the Higia V0 was created with Fusion 360® 3D modeling software (Autodesk, USA) and saved in an STL file (standard tessellation) for additive manufacturing. In the prototyping cycles, the STL file was converted into a G-code file using Simplify3D® slicing software (Simplify3D, USA). The polylactic acid (PLA) filament (Material 3D, China) was used to manufacture the frame in a 3D printer Stella 2 (Boa Impressão 3D, Brazil) using the FDM process. The G-code is the language used by the computer to communicate with the 3D printer information of quality control such as printer’s speed, which affects the production time, printer settings (nozzle diameter and position), printing settings (3D printed layer height and piece dimensions) and filament settings (type, color, diameter, and density). At the end of this phase, the Higia face shield model was ready to be mass produced.

2.2 Manufacturing of the Higia face shield using the fused deposition modeling (FDM) and the injection molding (IM) processes

To produce the Higia face shields using the additive manufacturing process, a FDM type 3D printer was required, with minimum printing area of 200 x 200 mm, filament (PLA), acrylonitrile butadiene styrene (ABS) or similar, transparent Polyethylene Terephthalate (PET) sheet or similar with thickness between 0.3 and 0.5 mm, and elastic bands. The set up FDM parameters were 5% full honeycomb infill, 0.3 mm layer height, 3 top solid layers, 3 bottom solid layers, 3 outline/perimeter shells, and 50 mm/s printing speed.

The process of face shield production using IM was based on the developed Higia design. The FDM process was used to prototype and test the injection mold development. This method required a favorable shape for melted material flow during the injection. Some parameters of the Higia model were changed to adapt to the metal molding production to be used in the IM machine. The mold is a structure of two parts: the cavity half of the mold and the ejector half of the mold, working together. The melted material (polypropylene) enters through a feed channel in the mold's cavity half and then it is hard-pressed, flowing through the machined ducts (guides) in cavity and ejector molds halves to form the desired part. After forming, the two parts of the molds are separated, the object is attached to the second mold and ejected from there, falling freely inside a collecting container in the machine. The qualitative comparison of both face shield production processes was based on Franchetti and Kress [38], who considered the pre-processing time, the processing time and the post-processing time, as well as production costs and advantages and disadvantages of use in a time of scarcity such as the COVID-19 pandemic.

2.3 Mass production and distribution

The Higia project website was created to recruit volunteers, to make available the open- source model of the Hígia face shield, and to receive requests of face shields donations from hospitals all over Brazil using the application Google form (Google, USA). Additionally, an account was created on Instagram (Facebook, USA) to provide training videos for the volunteers and to disclose information regarding the face shield donation progress. A crowdfunding campaign was created to raise funds for financial support for material purchase for FDM and IM processing and logistics.

The mass production of face shields was launched in two phases. The first one was carried out using FDM, and in the second phase relied on the IM process. The first phase accounted on a network of volunteers grouped into 3D printing production hubs all over the country remotely coordinated by the central hub in the city of São Paulo due to the quarantine lockdown. A logistics system was created aiming at material delivery, to coordinate the distribution of the 3D-printed frames, assembling of face shields, and supplying to hospitals according to the demand**.** The second phase was carried out by a partner company, and deliveries in remote regions were made by sea and air transportation.

3. Results

The frame of the Higia V0 has the shape of two arcs attached by their ends and united in a single piece with four anterior square pins for visor fitting, and two posterior round pins for the fixing of the frame to the head using a rubber band (Fig. 3).

Several changes were implemented in the frame of Higia V0 during the prototyping cycles**.** First, two strips were modeled to adjust the frame on the user's head (1); the angles formed by the union of the two bands were smoothed to facilitate cleaning (2), and the name “Higia” was imprinted (3) (Fig. 4a). However, the strips were fragile and broke during testing with users. In the second prototyping cycle (Fig. 4b), the shape of the anterior pin was changed into a hook to avoid detachment of the transparent sheet during face shield use (1); the distance between the pins was adjusted to ensure fixing and adjustment of the transparent sheet (2); The strips were remodeled for strength (3); The imprinted name “Higia” was removed to make cleaning easier and replaced by a triangle to indicate the position of use (4); the frame thickness was changed from 15 to 10 mm (5), and the frame type was changed from square to round (6). However, through the FDM process using PLA, the strips were not strong enough and were replaced by two elastic bands. In the last prototyping cycles, the distance between the two ends of the frame were increased from 101 to 128 mm, and the pin for the elastic band was changed for safety (Fig. 4c).

In the additive manufacturing production, the frame printing time was about 90 minutes (Fig. 5a, b). For the face shield assembling, the transparent sheet was cut and perforated with a conventional sheet hole puncher according to a layout (Fig. 5c). Each hole was fitted into the anterior frame pin and an elastic band was used to attach the head protector (Fig. 5d). The assembled face shield Higia has a full-face length with outer edges reaching the tip of the ear, including chin and forehead protection. It is low-cost (U$ 0.75), light (frame 16 g, assembled 43 g), flexible and resistant, one size fits all, comfortable, disinfectable, and it allows repeated reuse several times (Fig. 5e, f). Higia’s open-source model of was available on the internet with a guideline for production and use [39].

The injection time of each frame in polypropylene was 25 seconds. The stripes of the original Higia 3D printed model, printed in the prototyping cycle and rejected for being fragile in the FDM method, was reincorporated in the IM model resulting in one flexible strip of good mechanical resistance (Fig. 6c). A transparent plastic sheet made of Polyethylene Terephthalate Glycol (PETG) with 0.5 mm of thickness was used to serve as the frontal sheet (Fig. 6d). The Hígia injected face shield manufactured under the IM process has the following characteristics: Easy to assemble and transport, low-cost (U$ 0.47), light (frame 29 g, assembled face shield 56 g), flexibility and resistance, one size fits all, comfortable and reusable (Fig. 6e, f).

The qualitative comparison of both processes, FDM and IM, to produce the Higia face shield is summarized in Figure 7.

In the first 11 days of the Higia project, almost 80% of the face shields orders were placed by the state of São Paulo, the initial epicenter of the pandemic in Brazil. In the second month, orders from other states started increasing, as the coronavirus had spread over south and southeast states also infecting Brazil's northern and northeastern states. In total, 61.6% of orders were placed by the state of São Paulo, and the remainder was distributed among the other 26 Brazilian states. Apart from São Paulo, the northern and northeastern states, such as Amazonas and Pará, had the highest percentage of orders. The logistic system created is presented in Figure 8. About 1,861 individuals volunteered, and 20 Brazilian 3D printing companies signed up for 3D printing and about 500 kg of filament donation. Through the crowdfunding campaign, the contribution amount of U$ 13,300 was collected for the purchase of filament, transparent sheets, payment of material of IM material, transportation, and other expenses.

With the collaboration of volunteers, 35,000 Higia face shields were produced through the FDM process, and the IM process resulted in the production of another 80,000 face shields by for four partner industries [40] (Fig. 9). The face shields were donated and distributed to public hospitals for emergency rooms, surgical units, oncology units, intensive care units, otolaryngology practice, and anesthesia units of all states in Brazil. These distributions reached even indigenous population in remote regions of the state of Amazonas [42]. Figure 10 presents the qualitative comparison of both processes (FDM and IM) in the face shield production.

4. Discussion

The high demand for PPE during the COVID-19 pandemic left millions of healthcare workers unprotected, endangering the functioning of the entire healthcare system. Most of Brazil's public healthcare institutions did not have enough PPE, and few of them had face shields, which were used only in high-risk areas. The Higia project was created on 20 March 2020 when the period of community transmission of the new coronavirus had started over the entire Brazilian territory, when the number of confirmed cases of COVID-19 had reached 904 with 11 deaths. Ten days later, the Higia project was distributing their first volunteers-produced 3D-printed face shields to hospitals, while Brazil's updated numbers were showing 4,309 confirmed cases with 139 deaths. After 13 days of production, 24x7, more than 10,000 face shields had already been delivered. Such data showed the great potential for rapid device production using 3D printing in an emergency. Many 3D printer owners, small business owners, startups, and university students took their 3D printers home to have around 1,000 face shields printed daily in production hubs in different cities. Due to the application of a design for the face shield frame as simple as possible the 3D printing of the frame was carried by volunteers without difficulties. The greatest challenge was the materials acquisition for production, as since the stores and shops were closed and the volunteers were under lockdown or social distancing measures, sometimes unable to leave their houses.

The logistics for production and delivery of face shields mass production during the confinement period in a country with continental dimensions like Brazil was a big challenge. An important factor was the possibility of delivery of 3D-printed face shields for hospitals rapidly and continuously despite the lower number produced. This problem was solved with simple delivery logistics trying to access the volunteer closer to the requesting hospital. The IM face shields production allowed an increase in the number of manufactured frames by 100 times, each day. However, this high production volume was accumulated in a single location, and the logistics of delivery from a single spot became a challenge.

4.1 Design and usability

Many countries around the world have used the FDM process to produce cost-effective medical face shields [35-36, 41-46]. However, due to process' heterogeneity, some devices have been produced with no standardized procedure or medical approval. Face shields were adapted for oral and maxillofacial surgeons [41] and the radiology sector [45] with a design that makes cleaning a difficult activity. Face shields with very thin frames are more fragile, they can break during transportation or use, and are less comfortable and reliable. However, some 3D-printed face shield are as good as commercial standard-models [36]. It is possible to define the practicality, and clinical suitability of 3D-printed face shields related to weight, printing time, and if it required assembling tools to find an ideal dataset to be used for printing, scalability, and economic efficiency [46].

The Higia face shield designed in this study meets general requirements and specific ANVISA standards to reduce the potential for autoinoculation by preventing the user from touching their face [23]. The main features of the face shield are space for safe air ventilation and comfortable and low weight head fixation that does not limit the user's movements. Despite the recommendation that the face shield should avoid an open area between the first and second arc of the frame (Fig. 3), a consensus was established to reduce this distance and leave the area open, reducing the 3D printing time from 5 to 1.5 hours. This design ensures adequate space for the use of additional equipment such as surgical masks, respirators, eyewear, among other.

In this study, the level of protection offered by the use of the face shield it was not accessed, but it is known that this device protects to reduce transmissibility below a critical threshold [22]. The acetate and PETg used in the visors are transparent with high optical clarity, providing a good physical barrier to respiratory droplets. Acetate provides the best clarity and is more scratch-resistant against chemical splash protection, and PETg offers chemical splash protection at a lower cost. The Higia face shield is reusable, a replacement transparent sheet can be found in office supply stores. For disinfection, cleaning the face shield with soap and water or another type of disinfectant approved by the hospital infection control service is sufficient. Sterilization using high temperatures or abrasive materials is not possible.

4.2 Qualitative comparison of FDM and IM processes to produce face shields

The main advantage of additive manufacturing is the design freedom that may be applied at any point in the process. The FDM is the most commonly used 3D printing method using thermoplastics materials, with ease of handling, rapid processing, simplicity, and cost-efficiency [25]. The final cost is reduced due to machine and material low cost, but the process shows some limitations [47], as filaments such as PLA and ABS vary in material composition, porosity, and environmental stability. Although no mechanical tests were performed with the 3D printed face shields in this study, it is known that mechanical properties such as tensile strength, Young's modulus, elongation at break, and impact strength are lower in an object that is manufactured under FDM process compared with the ones under the IM process [48]. However, the mechanical stress that a face shield receives is extremely low, and although the facial protector produced by IM has better quality, both have a comparable functionality level.

Even though some authors claim that the FDM is a slow process and not suitable for mass production of face shields [35,43,46], the IM process, in contrast, requires skilled operators and relatively costly materials and equipment to be carried out. None of the additive manufacturing technologies is yet able to practically replace IM for medium- and high production volumes [49]. However, this study showed that low-volume production of a network on volunteers using the FDM process may offer an alternative for short lead times and a decreased overall production cost. While IM allows producing a large number of parts in a short period time, the distribution through a continental country like Brazil takes a long time, making it difficult to fulfill large orders in a quick fashion, regardless of production method. Despite not being as fast as IM processes, the FDM method allows the at-home, on-demand manufacture of face shields by a broad spectrum of users [46]. It is also possible also to have multiple frames printed at the same time to decrease production time using stacked frames. In this study, it was not possible to calculate the effective cost of FDM process production, as different 3D printers and filaments were used. A comparative analysis should be based on cost regarding the purchase of the manufacturing equipment, material, labor, and other costs.

This study showed the viability of using the FDM process in low cost 3D printers for rapid modeling and the production of small batches of face shields by volunteers with a simple process that can be organized for larger-scale production. Due to the support provided by 3D printing, the delivery of face shields started first, whereas the IM mold was still being produced, which the allowed for large-scale production. The FDM process allowed daily deliveries while the IM process allowed the production of large quantities in a short period time and it may be the best option for the production of a large quantity for remote areas that do not have access to 3D printers. This project shows how the FDM process allows small scale decentralized production of consumer goods at a pandemic situation as a response from civil society, allowing assistance to hospitals in need [50]. The results highlight the role of the “maker” or “citizen supply chain” community across the world, with collaborators from industrial and academic institutions, in a network, in a short period, to donate face shields to healthcare professionals [36]. This mobilization happens mainly due to the commotion and the sense of unity that is ongoing during the pandemic. Since the STL file of the Higia face shield was made available on the internet, many people in other countries such as Israel, Portugal, Jordan, Poland, Germany, the USA, and China have also produced face shields. It comes to show the accessibility and possibilities of integration and collaboration that 3D printing can promote.

5. Conclusion

In a situation such as the current COVID-19 pandemic, both FDM and IM processes are suitable for mass production of medical face shields. Once a committed network of volunteers is formed in strategic regions, the FDM process allows for a fast daily production of face shields. On the other hand, the IM process is proven to be the best option for large scale production and delivery to remote areas that have reduced access to 3D printers. The current study is the first one to perform a qualitative comparison between both manufacturing processes with the large-scale production of face shield. The 115,000 produced devices were donated and distributed to support the healthcare system during the COVID-19 pandemic in Brazil.

6. Abbreviations

ABS: Acrylonitrile butadiene styrene; ANVISA: National Health Surveillance Agency; CAD: Computer-aided design; CDC: Control and Prevention Center; COVID-19: Coronavirus Disease 2019; FDA: Food and Drug Administration; FDM: Fused Deposition Modelling; ICN: International Council of Nurses; IM: injection molding; PPE: Personal protective equipment; PETg: Polyethylene Terephthalate Glycol; PLA: Polylactic acid; STL: Standard tessellation; SUS: National Health System WHO: World Health Organization.

7. Declarations

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Figures

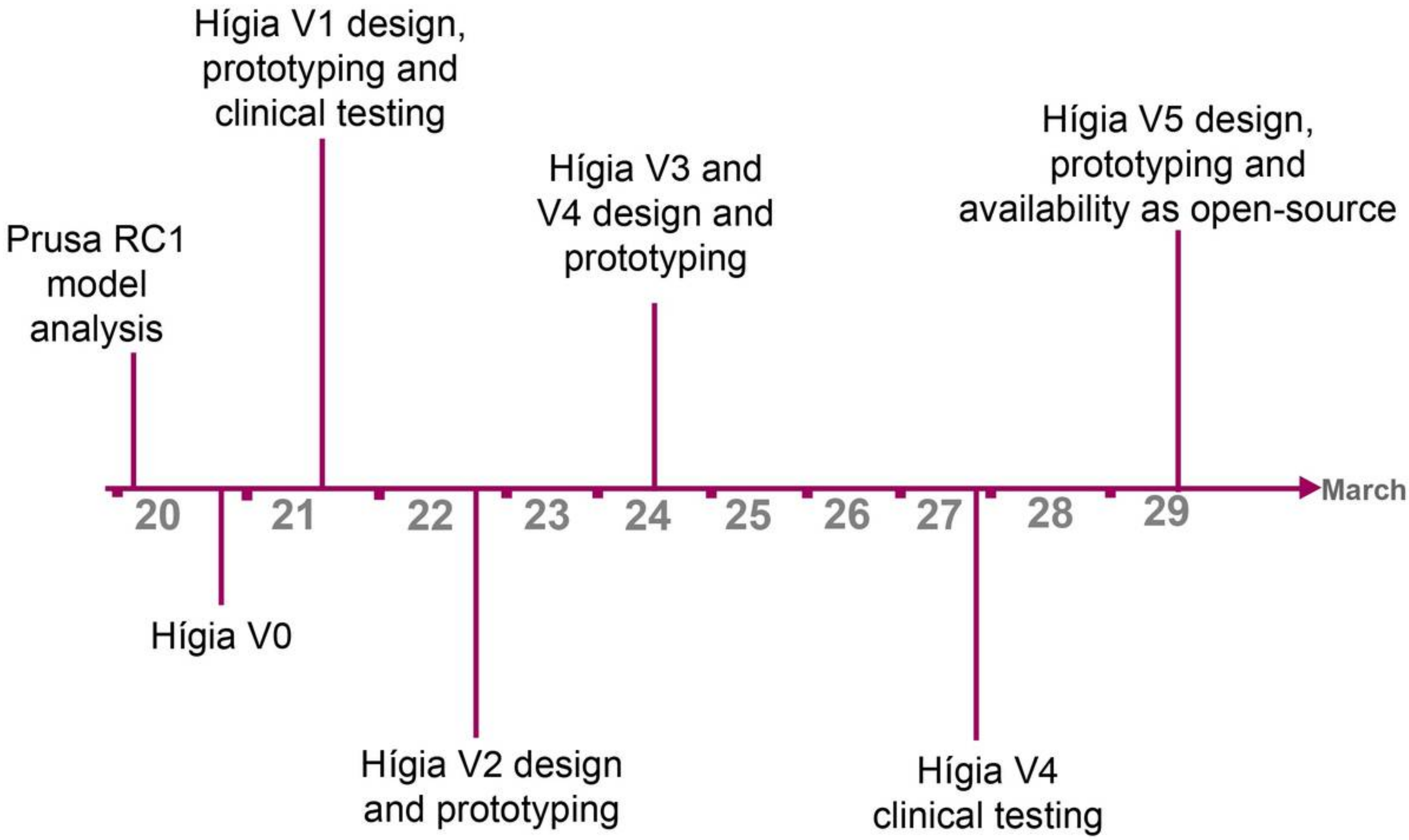

Figure 1

The timeline of the Higia face shield design development. Elaborated by the authors.

FACE SHIELDS REQUIREMENTS AND CONSTRAINTS

MEDICAL	3D-PRINTING
- Comfort. - Safe use. - Optical quality (transparency). - Low weight. - Hypoallergenic and non-toxic for skin. - Ease of sanitation with in-water and soap, 70%-alcohol or other disinfectants.	- Process: FDM - Material: Thermoplastic filaments, PLA* and ABS*. - 3D printer with a minimum table of 200 x 200 mm. - 3D printing time < 2h - Ease of printing. - Minimal filament usage. - Mechanical resistance of the frame (resistant to bending breaking).
ANVISA	**PRODUCTION**
- No protrusions, sharp edges, or any type of defects that may cause discomfort or injury to user. - Stability during use. - Adjustable straps/ self-adjusting (10-mm wide). - Visor preferably made of transparent material with minimum 0,5 mm thickness, 240-mm width and 240-mm height.	- Design: as simple as possible. - Materials: accessible and low cost. - Technology: as simple as possible. - The number of steps, pre-/post- treatments must be minimized.

Figure 2

Face shield requirements and constraints defined to meet medical needs, 3D printing, ANVISA standards [23], and production logistic.* Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), and Brazilian Health Surveillance Agency (ANVISA).

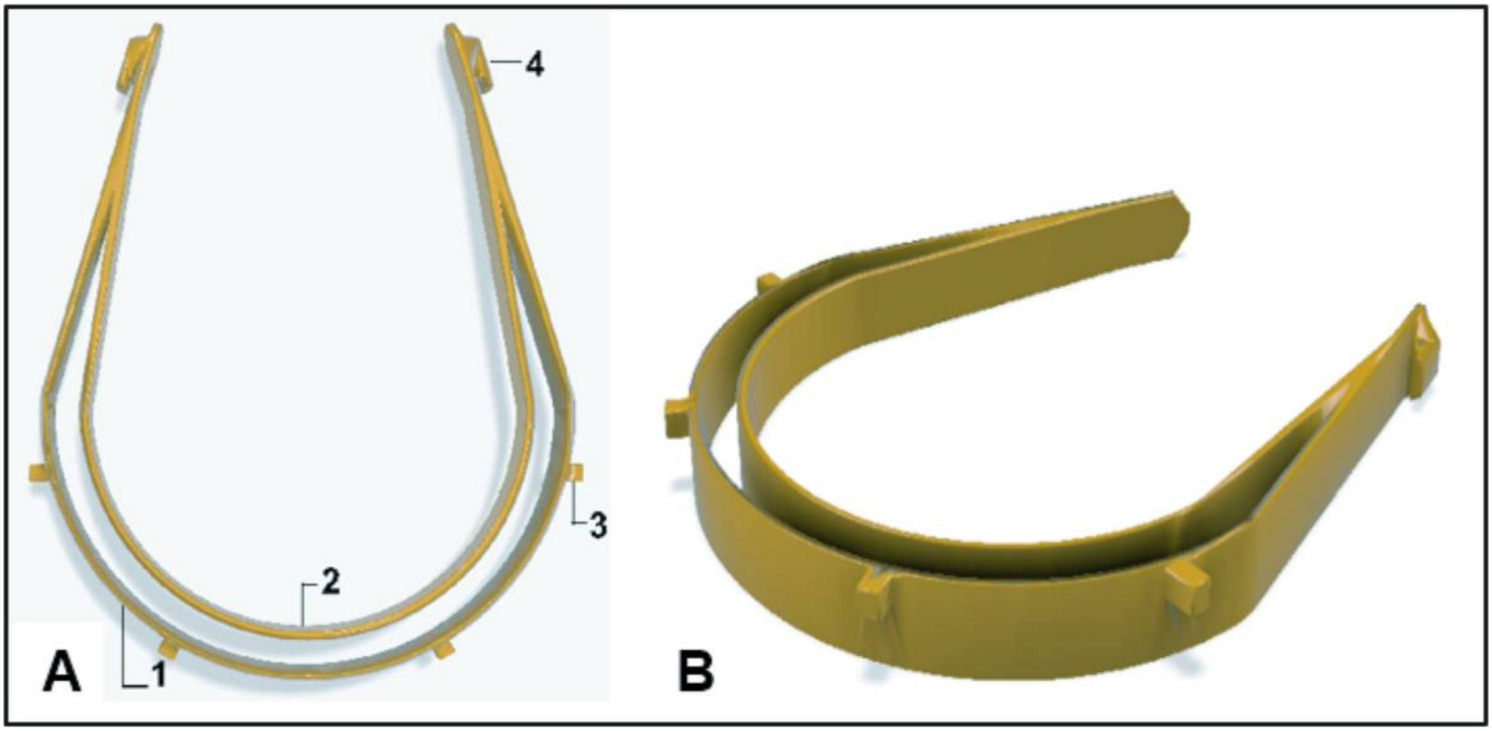

Figure 3

3D representation of the frame of Higia V0, superior (A) lateral (B) views. The main parts are: 1. The first arc, 2. The second arc, 3. Anterior square pins, 4. Posterior round pins.

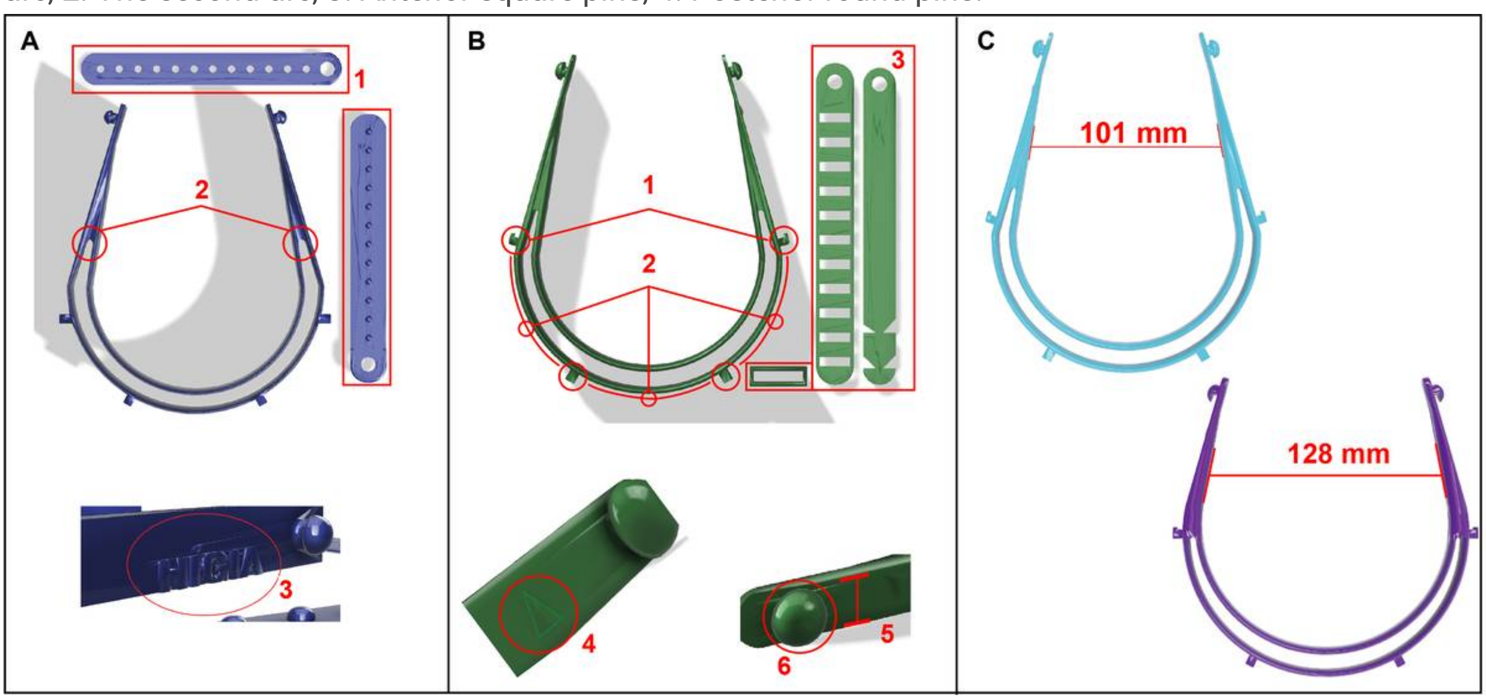

Figure 4

Prototyping cycles and clinical testing carried out for Higia V1 through Higia V5 face shields.

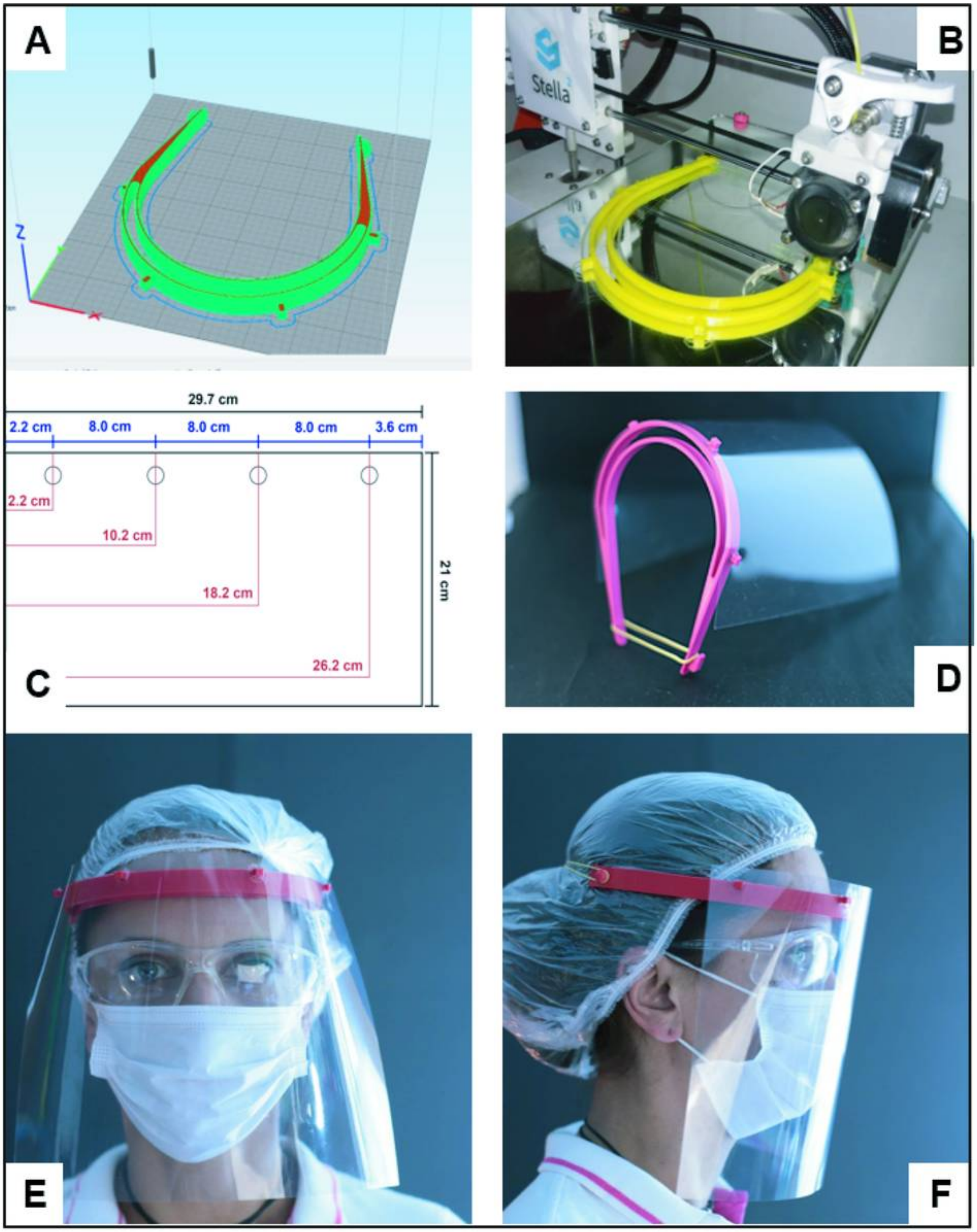

Figure 5

Higia face shield production process through the Fused Deposition Modeling (FDM) process. A) 3D model of the frame. B) 3D printing process of the frame. C) The layout of the transparent sheet. D) Assembled face shield (frame, transparent sheet, and elastic band). Frontal (E) and lateral (F) views of a user with the Higia face shield.

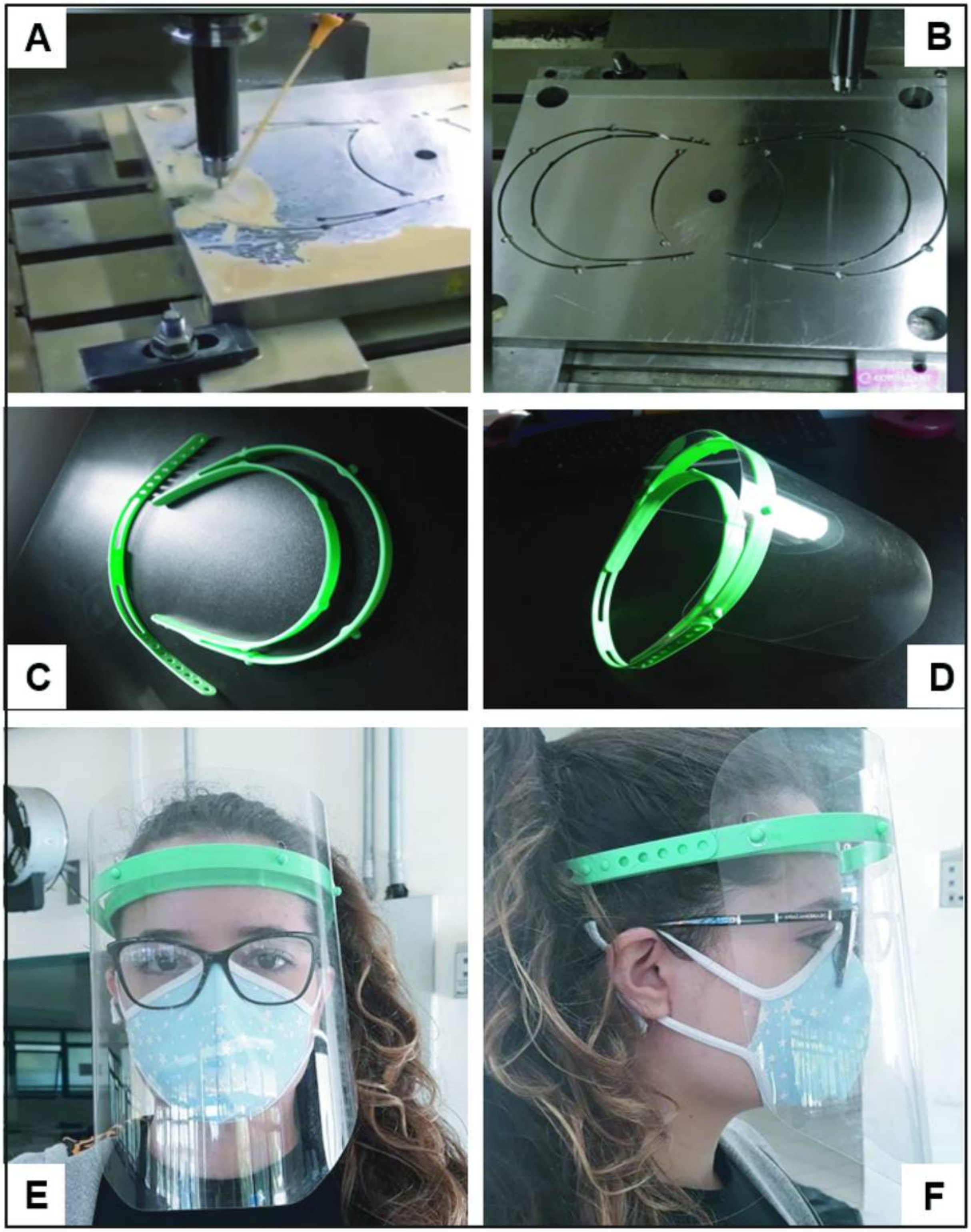

Figure 6

Production process of the face shield Higia through the plastic injection molding process (IM) (Coral Dent company, Brazil). A) Metal mold production. B) Metal mold. C) Face shield frame. D) Assembled face shield. Frontal (E) and lateral (F) views of a user with the face shield.

MAIN CHARACTERISTICS	ADDITIVE MANUFACTURING (FDM)	INJECTION MOLDING (IM)
Setup time to start the production	Few tooling and minimal labor (less than 30 minutes).	The time to produce and prepare a mold range from 2 to 6 days, depending on its complexity. It requires significantly more labor
Setup time during the production	Low cost 3D printers may require observation during printing, in addition to starting the machine after printing each part and filament change.	The injection molding machines run unsupervised once set
Post production finishing	Depending on the print quality, it may require burr removal and part filing	It does not require finishing
Quality of the produced object	Depends on parameters related to the type of 3D printer and the ability of the operator to adjust the parameters	The produced parts present homogenic quality
Production time (design and build)	Medium (10 per day) *	Fast (2,000 per day)
Energy cost of systems	1200 W in a 12-min warm-up and 300 W during runtime.	3000 W throughout the runtime, with an average setup of 120 min (The production of a mold may take up to 50 hours and machine preparation could take over 10 hours).

Figure 7

Qualitative comparison of the main characteristics of the manufacturing processes Fused Deposition Modeling (FDM) and Injection Molding (IM). The table uses key concepts found in reference [38]. * It depends on the printer’s default speed, size of the nozzle, extruded layer height, and size of the object being printed. It is important to maintain a balance between printing time and quality adjusting these parameters.

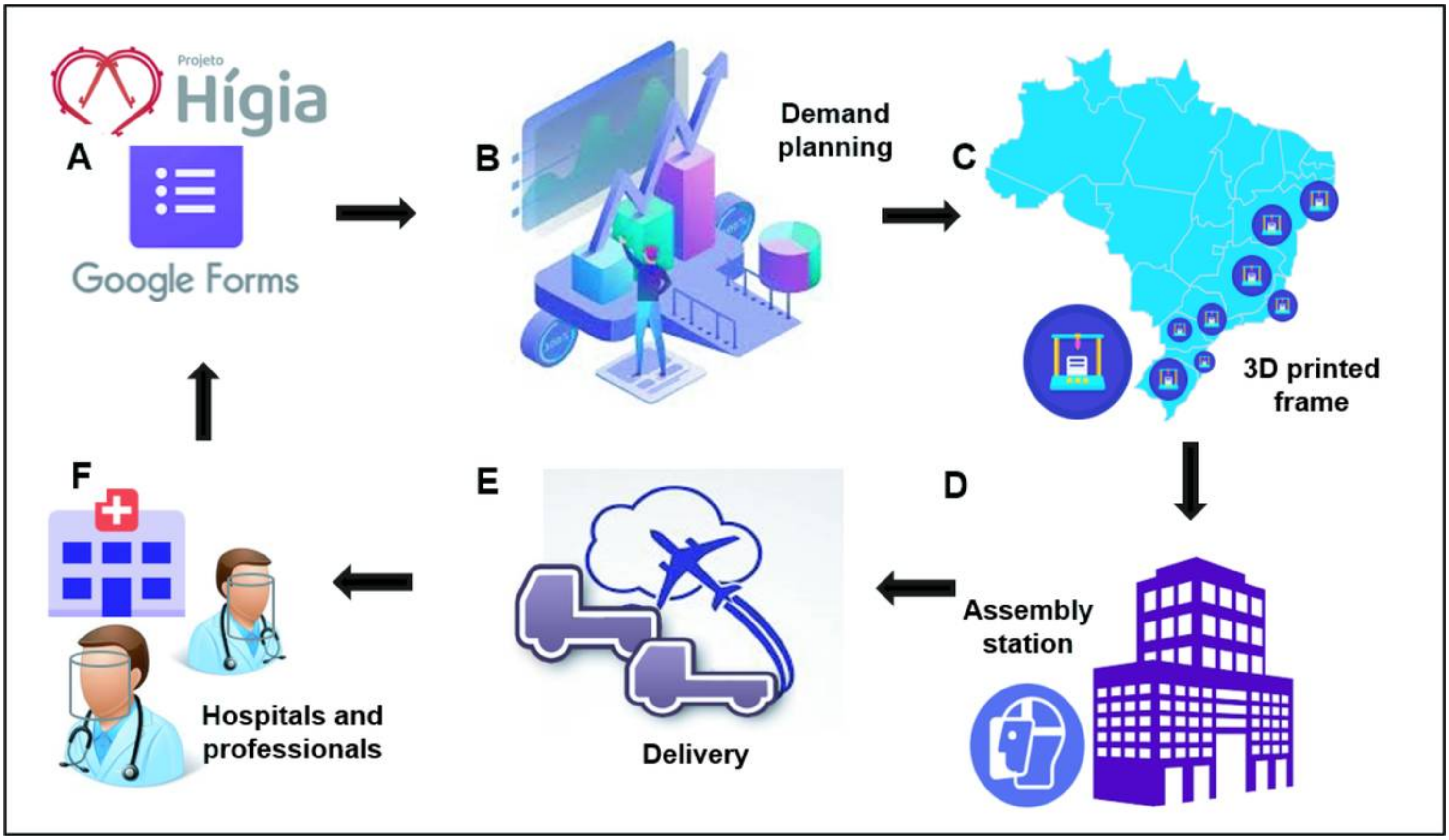

Figure 8

Logistics system of Higia's 3D printed face shield production hub. A) The analysis of face shield requests collected on the Higia website using a Google form; B) Definition of required demand of face shields by the planning sector, use of the resources acquired through crowdfunding and donations for purchase and transportation of transparent plastic sheets and rubber bands to the assembling hub; C) Request and collection of 3D printed frames from the manufactures and delivery to the assembling hub; D) Assembling of the Higia set that include a 3D-printed frame, a transparent plastic sheet, two rubber bands and an instructions manual on assembling and cleaning of the face shield; (E) Transportation of the Higia set by partners transportation companies; (F) Delivery of the Higia set to the public health institutions.

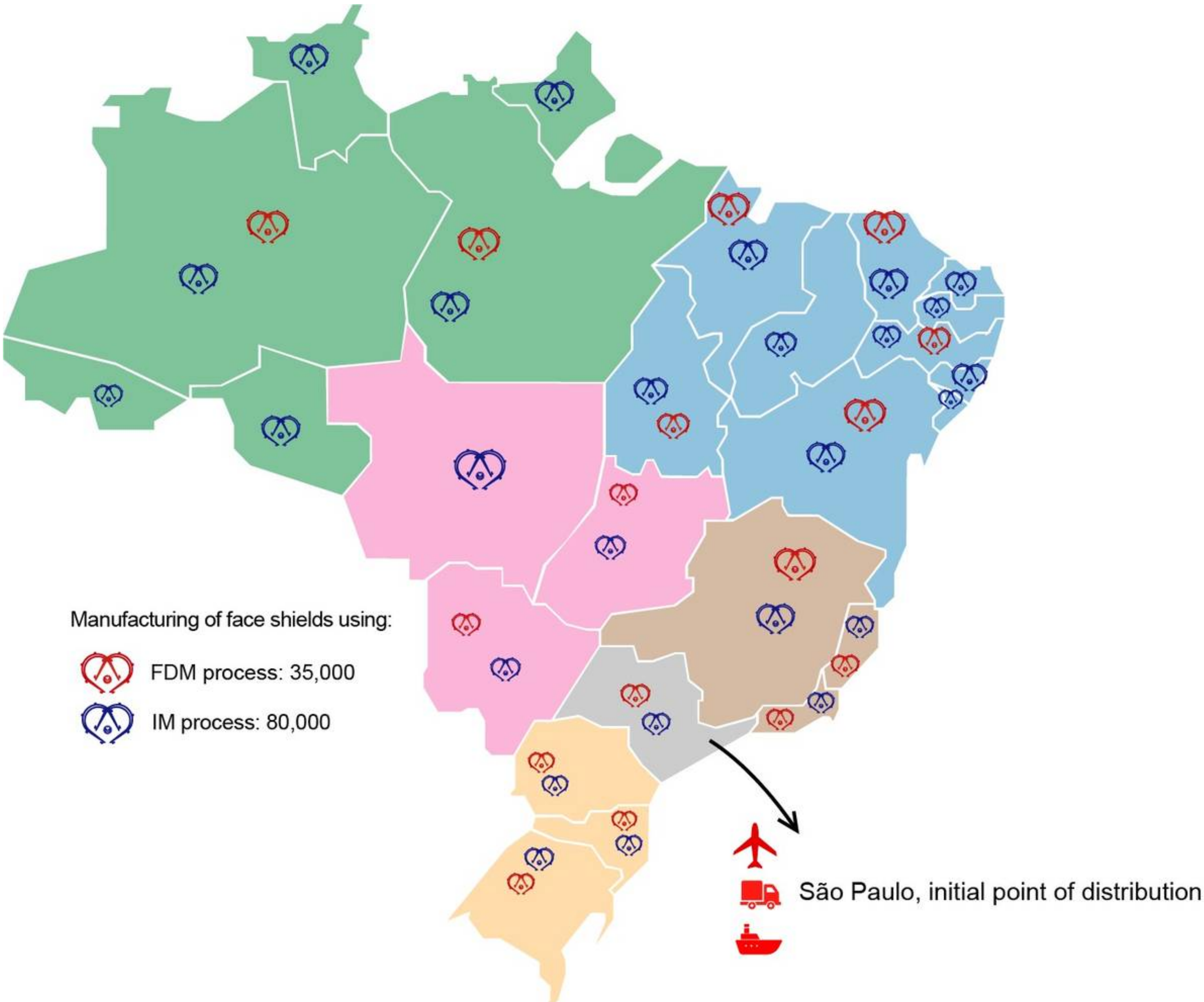

Figure 9

Distribution of 115,000 face shields in Brazil: 35,000 produced through the Fused Deposition Modeling (FDM) process, and 80,000 produced through the Injection Molding (IM) process. The distribution point was the city of São Paulo, and all regions were served by land, sea, and air transportation. Brazil is the fifth largest country in the world, with roughly 4,350 km from north to south and from east to west. The map was elaborated by the authors.