Confronting COVID-19 - The case of PPE and Medical Devices production using Digital Fabrication at PUC-Rio

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ABSTRACT

At the end of 2019, the first cases of COVID-19 were registered. As the disease spread across continents culminating in a pandemic, countries suffered from a shortage of personal protective equipment. In Brazil, the first case was recorded on February 2020. This study aims to describe the experience of creating an interinstitutional network to meet the pandemic's demands and the experience of transforming an academic design laboratory into space for the production of personal protective equipment using 3D printing and laser cutting techniques. The actions described in this study, made it possible to meet the high emergency demand for PPE in the city of Rio de Janeiro, as well as the construction of knowledge both within the scope of building networks to solve complex social problems and about the possibilities of production in an academic environment. The work also addresses the importance of the divulgation obtained by the project -specially on national TV broadcast and social media – as a way to raise society's awareness of design professionals work.

Keywords: COVID-19, PPE, 3D printing, mask, face shield.

INTRODUCTION

In December 2019 cases of an unknown viral disease appeared in Wuhan, Hubei Province, China. These records corresponded to the first cases of COVID-19 (WHO, 2020a). By June 2020, the disease had been diagnosed in more than 7,800,000 people and had claimed 430,000 victims (Johns Hopkins University, 2020).

As the epidemic spread through the various countries, WHO issued guidance on the protection items needed by health professionals working to assist those infected with COVID-19 (WHO, 2020b, WHO, 2020c). The scientific community also made recommendations on the correct use of these items (Ortega, 2020).

The demand reached 100 times more than normal. This high demand, panic buying, and inappropriate accumulation caused a shortage of personal protective equipment (PPE). Prices were twenty times higher. The WHO then, issued a warning asking industries and governments to increase production by 40% to meet global demand. This shortage has left front-line health care professionals without the proper equipment to work on the care of

COVID-19 patients, making them more vulnerable to get infected. For a proper protection it was estimated that these professionals needed about 7 to 10% of surgical masks world supply. The WHO alert also addressed widespread market manipulation with stocks being sold by the highest bidder, causing panic and diplomatic incidents (WHO, 2020d; Boseley, 2020).

Research groups and people involved with 3D technologies and digital manufacturing found the use of 3D printing technology as a way to mitigate the shortage of PPE caused by the pandemic. Initiatives began in the first countries affected by the COVID-19 pandemic in the world like China, Spain, and Italy. As soon as it was possible, studies on the development of equipment - such as face shields (AMIN et al., 2020; SAPOVAL et al., 2020) and masks (SWENNEN, 2020) - were released.

3D printing technologies were already being indicated for use in humanitarian contexts for hyperlocal production. The in-site production of resources needed - such as in developing country's health clinics and refugee settlements - is considered a solution to the logistical and supply chain problems involving humanitarian aid (James & Gilman, 2016; Tatham, 2014).

Considering the history of the PUC-Rio's Núcleo de Experimentação Tridimensional – NEXT - in projects related to additive manufacturing in medicine and health (DOS SANTOS et al, 2019; DOS SANTOS et al, 2013; FRAJHOF, 2015), the mobilization was almost immediate in order to support the emergency response in the lack of PPEs in Rio de Janeiro's public health system.

The objective of this study is to describe the experience of the Department of Arts & Design of the Pontifical Catholic University of Rio de Janeiro – PUC-Rio team in the elaboration of an inter-institutional network and the transformation of an academic laboratory into a PPE production space to supply the city's medical teams demands.

1. NETWORK CONSTRUCTION AND PPE PRODUCTION

In early March, a meeting at *Palácio Guanabara* - Rio de Janeiro's state government headquarters - was attended by some public and private institutions researchers and representatives, as well as members of the state health department. This meeting discussed how it would be possible to build a local and agile production of PPEs and other medical devices due to the lack of world supply for these items.

In order to answer these need an inter-institutional network was established among the Pontifical Catholic University of Rio de Janeiro (PUC-Rio) - through the Department of Arts and Design (DAD-PUC-Rio) - the Industry Federation of the State of Rio de Janeiro (FIRJAN) and the Federal University of Rio de Janeiro (UFRJ) - through the Clementino Fraga Filho University Hospital (HUCFF). The main objective of these Network was to develop, assess, produce, and distribute the PPEs to reference hospitals and institutions in the fight against the disease caused by the new coronavirus (COVID-19).

Despite the extensive manufacturing infrastructure offered by both PUC-Rio and FIRJAN, it was soon realized that the challenge would be quite high. The estimated demand from the health department for each PPE model - such as N95 masks, face shields, goggles - was in the tens of thousands, remarkably high numbers, even for such infrastructure. Thus, it was

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sought to understand which PPE models were simplest to produce, as well as the amount of labor on research and development for them to be available.

Considering the possibilities of infrastructure and personnel, the the administrative officers from the University were asked for permission and support for the initiative, which was accepted immediately. Consequently, this inter institutional network was put into practice so that it was possible to act on several fronts. However, regarding the huge amount of PPE needed by the medical teams, and the physical limits from both digital manufacturing and involved laboratories, it was decided to plan and put into practice a long discussed process - but little performed -: network manufacturing.

Several groups were formed in the most diverse social medias. In these groups were not only representatives from research institutions, but also members of civil society from various backgrounds - such as doctors, designers, engineers, chemists, among other specialties - with a common characteristic, all interested in the maker movement and willing to help in this effort. Thus, a form was shared in order to map out the technologies available by the group. More than a hundred responses were promptly received from makers and manufacturing spaces in Rio de Janeiro, putting their machines and facilities available to support the local response. From this mapping it was possible to visualize the size of the network, the location of members, and the main technologies available for the manufacture of PPE and medical devices. Considering the data obtained (figure 1), we choose to work especially with the Fused Deposition Modeling (FDM) and laser cutting due to its huge availability and low costs.

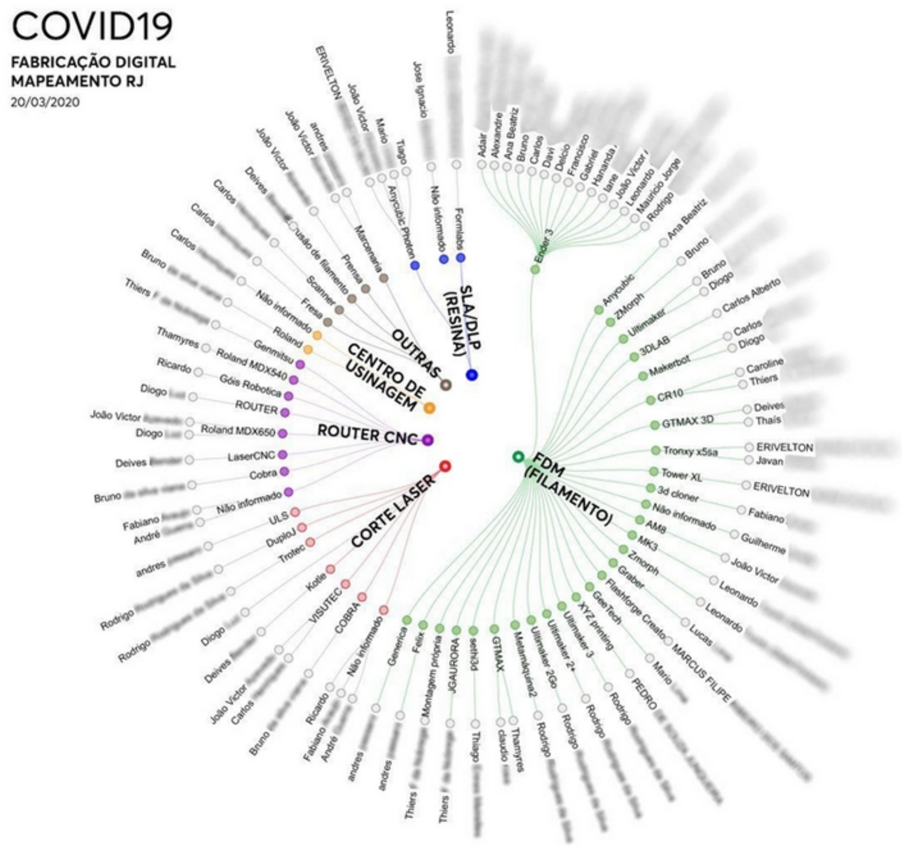

Figure 1 - DataVis obtained through the form sent via internet until March 20, 2020 (source: Dr. Barbara Castro, PUC-Rio)

After this mapping the makers and companies which owned the machines were contacted and inscribed in an internal list. After making sure if they were really interest in participating, they were organized by city areas and material need so it was possible to

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projecte how much material should be order and how many pieces could be produced per week.

The development of these kind of networks brings a lot of advantages such as: experimentation agility, production volume, creative contributions, and cost reduction. However, there are some disadvantages such as information overload, overlapping solutions and egoic conflicts in decision making.

Because of the need for solutions in a small period of time, a lot of design proposals were sent by the whole community. The greater part of them were very raw. Some of them were basic first concepts, which lack on minimal design aspects such as fittings, material availability, inappropriate manufacturing processes and so on. The great majority were not even been prototyped. Nevertheless a constant in this process was the designers' naming and treating them as "miracle solutions" or "the best solution ever", when clearly it was just initial ideas, despite their egoic perceptions – a bad, but real, habit on Design's practice. This kind of mis happenings were solutioned applying a design methodology – developed and used at DAD-PUC-Rio - as a guide for the future decisions: Social Design method.

2. SOCIAL DESIGN

The practice of the Arts and Design department of PUC-Rio is based on Social Design (FABIARZ & RIPPER, 2011; ARAUJO, CÔRTES, & FARBIARZ, 2020), a method that seeks to understand the reality of a certain social group and, based on conviviality and dialogue, develop solutions that enrich local relationships and improve the interactions which characterize those Space. Therefore, it was understood that the role of DAD-PUC-Rio would be a glimpse at the local Space, in order to organize this network and define some premises for the development of the action. Following this path, the developed objects made much more sense in the local health units' interactions.

As usual in the process of DAD-PUC-Rio, it was first defined that we would not "reinvent the wheel". Knowing that the pandemic had already hit other countries hard, solutions which were already in use in these places - and that already had some validation by agencies and medical staff - were sought in order to understand what and how they could be adapted to the reality of Rio de Janeiro. A pilot production was then organized for each item found. With this production it was possible to define its degree of feasibility within the available Network infrastructure. Other important points that were observed on these solutions were the real need at the Rio de Janeiro's front and whether it was in accordance with the national standards of both the Brazilian Association of Technical Standards (ABNT) and the National Health Surveillance Agency (ANVISA).

The second step of the process was the validation of the solutions in the health units. As previously mentioned, it is of fundamental importance the understanding of the object in its real use, in the Space where it will be used, by the people involved in the whole process of its activation. The concrete reality where it will be used is, many times, very distant from the reality of the designer. Therefore, a huge effort should be made to understand the interaction between object x action x user x place. This awareness is a sine qua non condition for the development of products that are, in fact, useful and that, in fact, comply with the interaction to which they were designed (MATTEONI et al, 2020).

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3. THE ITEMS

Based on the requirements, several pieces of equipment were obtained in order to understand what was needed in the health centers and could be produced by the network to meet the Rio de Janeiro reality of the pandemic. A lot of equipment were printed and tested, both in lab environment as in field, and thus the focus was set on the following items:

Face shields: after a series of tests with several models available on the Internet, the model developed by Josef Prusa (www.prusa3d.com) – which fulfils European Community health standards - was used as the basis. This model required few changes, such as the type of material (originally designed for PETg, was changed to PLA, aiming at a higher production speed) and a small change in the laser cutting file of the visor (aiming at facilitating assembly by users). The RC1 lite model (a RC1 remixed by a user in Josef Prusa's own repository) and the RC3 model were used, aiming a greater comfort for the different head sizes.

Figure 2 - health professional using a face shield based on RC3 model by Josef Prusa. (source: Luiz Eduardo Carnevale)

Goggles: Although it is an item of fundamental importance, few models were found available. In view of the ease and agility of production, the "lunnette covid-19" model - made available by the user RAIDEN39 in the Cults3D.com repository - was used as a basis. This model required heavy changes in order to be validated by health professionals. Its main structure was totally redesigned - based on the anthropometric features of the Brazilian people - and its lens was also modified in order to facilitate assembly, as well as improve the sealing at the interface with the forehead and the cheeks.

Figure 3 - Health professionals wearing the goggles developed by DAD-PUC-Rio. (source: Raphael Bertani)

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- N95 Mask: several models are available in several repositories. A great number were printed and tested; however, none are in accordance with the Brazilian standards of ANVISA and ABNT, especially regarding sealing with the face and the filtrating element. Hence, a complete redesign was conducted, which at this moment awaits a series of tests with the regulatory agencies.

Figure 4 - DAD-PUC-Rio Team member using the under development TPU/PLA 3D printed N95 prototype. (source: authors)

Video laryngoscope: In view of the need for ventilation for most COVID-19 patients, faster, simpler, and cheaper alternatives to regular video laryngoscopes - whose value may exceed tens of thousands of dollars - have been sought. The solution was based on the Air Angel blade model. Like the other devices, a series of modifications were necessary to meet the local reality in Rio de Janeiro. At the moment, this object is in the validation phase by the medical team and regulatory agencies.

Figure 5 - Video laryngoscope model developed by the DAD-PUC-Rio team based on the Air Angel setup. (source: authors)

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Swab: The need for mass testing has been a standard set by the WHO since the first moment of Pandemic. The PCR test is considered the most reliable for assessing the patient as infected or not. This test requires the use of at least three swabs (a small tube with absorbent material at the tip) that collect mucus from the patient's nose and throat for laboratory testing. Although apparently simple, this device has disappeared from the market especially because the absorbent tip material (Rayon) was missing worldwide. Among the solutions found on the web, the model developed by FormLabs, draws attention for its ease of production and for having been validated in several North American hospitals. This device has already been validated by the HUCFF team and is currently awaiting the implementation of a new stereolithography printer at DAD-PUC-Rio.

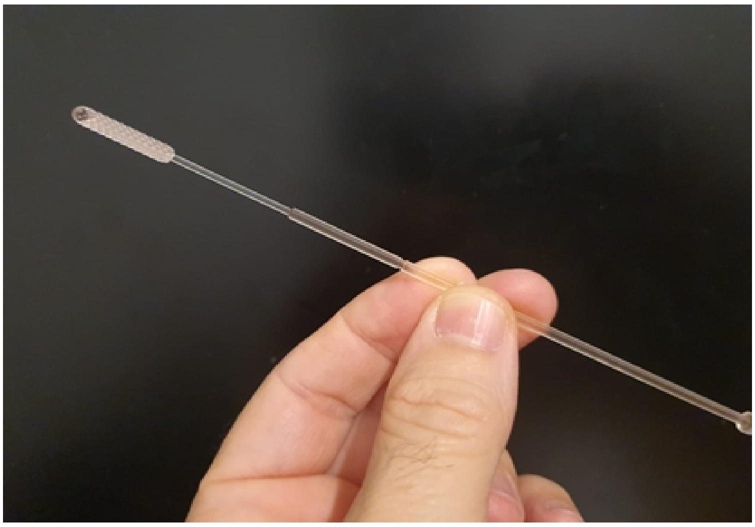

Figure 6 - Swab developed by FormLabs, validated by HUCFF team. The production is under implementation by DAD-PUC-Rio. (source: authors)

4. ASSESSMENT

An assessment network was organized. After being produced, the material was presented to a physician - general practitioner and post-graduated in Design - for evaluation of usability, safety, and visibility. With this initial validation, a group of researchers, technicians, and design students evaluated the objects in relation to their form, toxicity, and sterilization method, as well as in which hospital environments it should be used and which health professional would use it (information obtained from HUCFF).

Figure 7 - Some of the PPE models sent for assessment procedures. (source: authors)

If the artifact was qualified and validated for use, a small pre-production batch was sent for use by the health teams at the Clementino Fraga Filho University Hospital/UFRJ, to be field tested in the COVID wing. In case of approval by them, the object was allowed to be produced regarding the parameters stablished by DAD-PUC-Rio Researchers.

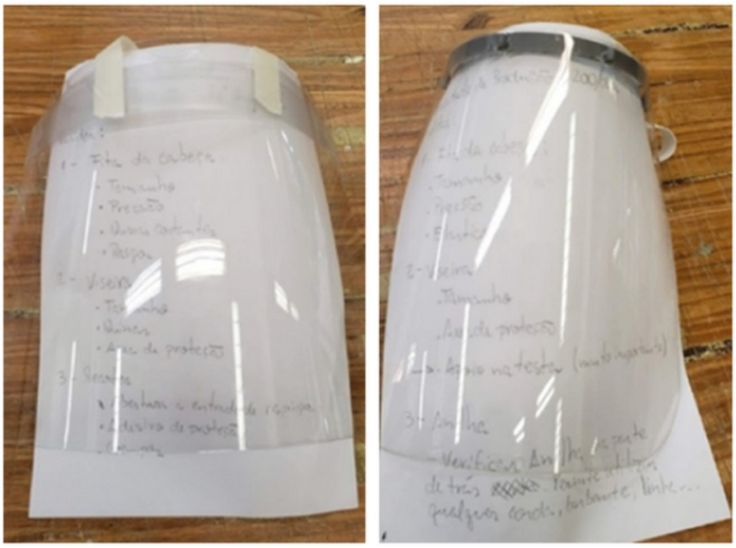

Figure 8 - Pre-production parts sent for validation at HUCFF. Internally we can see some of the questions to the health team which received the parts. (source: authors)

All information necessary for its production, assembly and maintenance was organized in a cloud-based folder, which was shared with all members of the network. The pieces were then produced in a distributed manner and later sent to the Laboratory for Models and Prototypes (LAMP), at Department of Arts & Design of PUC-Rio. Every week the network logistics responsible called al the makers and companies which were enlisted to know how many pieces they made and how much material they need to continue printing more objects. When the member had at least 20 units, they entered on the logistic route, which retrieved the ready parts and delivered more material to continue the production. All the ready items were sent to the LAMP

In the lab, the pieces were selected - as ready, finishing need, or disposable - organized by model, and then arranged in kits - along with other pieces produced - to be sent to health centers.

5. TRANSFORMING THE ACADEMIC LABORATORY INTO A PRODUCTION ENVIRONMENT

The LAMP is a workshop lab mostly used by the students of the Product Design Bachelor's course, but it is open to other students. The laboratory staff consists of three employees, six interns and an average of fifteen monitors during the semester. In describing the space, Câmara (2020), divided it into three main areas: workbench area, machine area and classroom. The workbench area was the main space in the laboratory occupied for production. The workbenches were reorganized and the three 3D printers available in the laboratory - at the time - were moved into space. Usually, the 3D printers are available for the students in a specific room, next to the computers with the software for 3D modeling and preparation of the print files. To these three printers were added five more bought by DAD-PUC-Rio, besides other five borrowed by other sectors of PUC-Rio, such as the Center of Telecommunication Studies (CETUC), which in addition to the machine ceded the employee Marcelo Balisteri, the Department of Informatics, teachers, alumni and partner schools. Besides developing, centralizing, and delivering the parts, LAMP also became a manufacture center of printed parts, being responsible for about 40% of the parts printed by the network. The whole laboratory had the following FDM printing equipment:

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- 6 Creality Ender 3 (printing area 235mmx235mm)
- 2 Ultimaker S2/S2+ (printing area 202mmx220mm)
- 1 Creality CR-10 S5 (printing area 500mmx500mm)
- 1 Cliever CL1 (printing area 120mmx120mm)
- 1 Felix 3.0 (printing area 240mmx205mm)
- 1 Makerbot Replicator 2 (printing area 285mmx153mm)
- 1 Voolt Gi3 (grabber i3) (printing area 200mmx200mm)

Figure 9 - Arrangement of 3D printers in the LAMP (source: authors)

The laser cutting space are located in the machine area. The laboratory has a room with a computer for file preparation and control and another separate room for the laser cutting machine. In the production of PPE this space was essential. Both the face shields and the goggles were produced using this technique.

For the production structure the lab was divided in two spaces: laser cutting space and printing space. The laser cutting space followed the standard layout of the laboratory, except for preparing the material to suit the dimensions of the laser cutter, which was cut into a specific space arranged next to the printing space. The print space was established in the workbench area. The workbenches were reorganized by islands to facilitate the manufacture and organization of the pieces. The scheme (figure 10), adapted from the Câmara study (2020), presents the organization of the lab for PPE production.

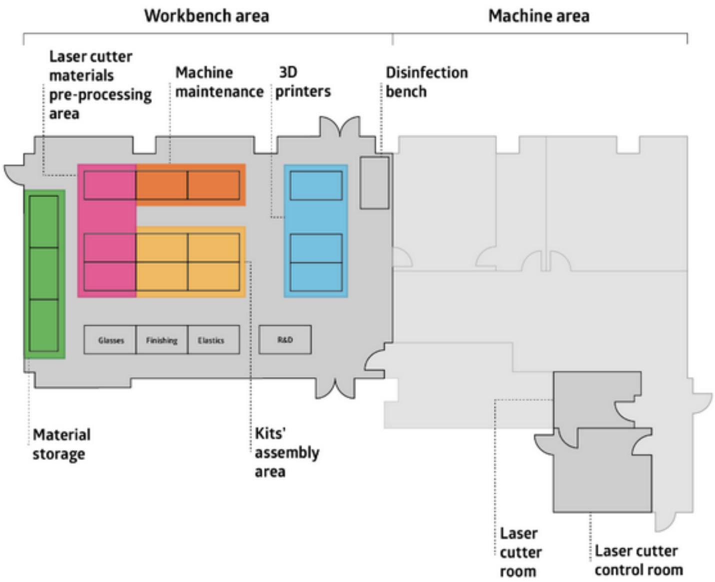

Figure 10 - Organization scheme for the PPE production at LAMP-PUC-Rio. (Source: elaborated by the authors adapted from Câmara (2020)

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The printing space was divided into specific areas to carry out the production stages. The central zone was occupied by the kit's assembly area and the 3d printing area. The material storage took three benches in the side of the main space, the same number for laser cutter material storage and preparation. Another two benches were reserved for machine maintenance. One bench corresponded to the space for models in research and development, another was used to cut and organize the elastic bands and next to this was the bench for the finishing procedures of the pieces. The glasses were organized and arranged on a separate bench.

Figure 11 - view of the central island where the kits are organized for distribution. In the background you can see the printing island and on the left the elastics cutting area and the R&D area. (source: authors)

Polylactic acid (PLA), polypropylene (PP) and acrylonitrile butadiene styrene (ABS) filaments were mainly used to produce the printed components of the devices. These materials were bought by the institutions and particular donators and then distributed through members of the network to be 3d printed. Face shields' and goggles' lenses were produced in PET-G (polyethylene terephthalate glycol-modified) 0.5mm thick, which is required by regulatory agencies. The production of these parts was all done at LAMP.'s laser cutter. All the materials were validated as per use, production, and sanitation.

6. DISTRIBUTION

The deliveries were organized according to the hospitals' demand. They filled a form in order to verify the applicant's information and the real need for equipment for the place. This process was complex from the very beginning given the lack of products on the market and the extreme urgency to obtain them. The team, sometimes, found itself in Sofia's choice, choosing which place to send, even knowing the general need.

To avoid an uneven distribution among health units, a method of allocation was developed to contemplate all but focusing first on protecting those professionals in direct contact with COVID-19 patients. The first PPEs deliveries was to the university hospitals. As those institutions were familiar to research and assessment protocols, these centers supported adjustments in production and effective evaluation of PPE quantities per health unit. With this information, a delivery priority was organized for the health centers based on the organization made by the state health department:

- Reference hospitals for the COVID-19 treatment
- Major Emergency Hospitals
- Basic Emergency units

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- Emergency medical services (SAMU)
- Basic Health Units and Family Health Units

Knowing that it would still not be possible to deliver 100% of the demand, each unit was contacted in order to inform the number of ICU and Emergency beds. With this number it was possible to count the amount of health professionals per bed in these areas -stated by law- and project a minimum necessary number for an immediate coverage of the most sensitive areas. The aim was to prioritize the professionals in high contact with the virus, and, thus, high risk of infection. Based on this data, each healthcare unit was informed about the quantity available, the priority of delivery and the day to collect.

The equipment was distributed in kits. The face shields were distributed containing the parts necessary for their assembly. The packages were organized containing 25 pieces of each item: 3D printed headbands, laser cut PETG lens and elastic strips for a better adjustment to the head. When delivering the equipment to the healthcare professionals, the team provided information about assembly, handling, and sterilization of the material.

Figure 11 – delivery kits (source: authors)

The researchers realized that the assembling of the goggles required excessive care to avoid breaking the PETG lens. Therefore, it was decided to send to the professionals the kits containing the glasses already assembled. Because of the volume, the glasses kits contained ten units in each.

Figure 12 – Delivery (source: authors)

7. THE DELIVERIES WERE ORMACHINE MAINTENANCE

Due to the extended use, the machines required constant adjustments and repairs which were not common when used for the laboratory main purposes. The adjustments and repairs consisted of everything from replacement of parts - such as extruder nozzles – to fine alterations for the use of different materials.

Taking into account the number of worked hours and the number of parts delivered, the individual maintenance cost per machine has been greatly low, with most of it being consumable parts replacement such as nozzles, thermistors, PTFE tubing and connectors for the Bowden extrusion system.

Important to note that in some of the replacement cases, the team used parts available at online repositories. The parts ware printed and used to repair the printers' broken components. A real example of "printers printing printers".

8. CONCLUSION

Like other countries affected by the COVID-19 pandemic, Brazil was one of the places where civil society and academia came together to meet the health professional's emergency demands on the Sars-Cov-2 fight front lines. The inter-institutional network, described in this study, made it possible to supply PPEs to a great number of health centers in the metropolitan region of Rio de Janeiro.

By describing the necessary processes for the development of this action at PUC-Rio, this study demonstrates the potential of networks structured between academia and civil society for the solution of complex social problems. The development of a large-scale emergency production established in an academic laboratory, such as LAMP, also provides important contributions about the expansion of the academy role in the solution of emergency social demands.

The solution to meet the demand for PPE through the use of digital manufacturing techniques, such as laser cutting and 3D printing, represents an important factor in the consolidation of this technology for end user products manufacturing.

Another important contribution of these initiative lies on the divulgation obtained by the project. The action developed was widely disseminated. The project was presented in one of the main TV news in the country and in many other broadcast shows. Social media's respected profiles and influencers helped spread this Design approach of the crisis. It was quite interesting because historically, designers face difficulties both in relation to knowledge about the possibilities of professional action and the perception of value about the profession. The elaboration of this action by the Department of Arts & Design of PUC-Rio - together with other sectors of civil society - highlights one of the main functions and capacities of the design professionals: gathering a variety of areas - such as medicine and engineering – and making the result of this union available to society throughout products and services. This logic demonstrates a wide possibility of action for the profession, and may contribute to raise society's awareness of design professionals work .

Some of the devices described in this study are still being developed to enhance and expand the possibilities of use. In future studies, the design process, and the iterations for the improvement of the equipment will be explained.

The city of Rio de Janeiro has approximately twelve thousand health professionals (TOKARNIA, 2020). Since March, the LAMP-PUC-Rio production made possible the distribution of around sixteen thousand faces shields and three and a half thousand goggles for the front-line professionals.

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