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COVID-19: Rapid prototyping and production of face shields via Flat, Laser-cut, and 3D-printed models

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Abstract: The use of personal protective equipment (PPE) has become essential to reduce the transmission of coronavirus disease 2019 (COVID-19) as it prevents the direct contact of body fluid aerosols expelled from carriers. However, many countries have reported critical supply shortages due to the spike in demand during the outbreak in 2020. One potential solution to ease pressure on conventional supply chains is the local fabrication of PPE, particularly face shields, due to their simplistic design. The purpose of this paper is to provide a research protocol and cost implications for the rapid development and manufacturing of face shields by individuals or companies with minimal equipment and materials. This article describes a best practice case study in which the establishment of a local manufacturing hub resulted in the swift production of 12,000 face shields over a seven-week period to meet PPE shortages in the North-West region of Ireland. Protocols and processes for the design, materials sourcing, prototyping, manufacturing, and distribution of face shields are described. Three types of face shields were designed and manufactured, including Flat, Laser-cut, and 3D-printed models. Of the models tested, the Flat model proved the most cost-effective (€0.51/unit), while the Laser-cut model was the most productive (245 units/day). The insights obtained from this study demonstrate the capacity for local voluntary workforces to be quickly mobilised in response to a healthcare emergency, such as the COVID-19 pandemic.

Keywords: COVID-19; personal protective equipment (PPE); medical face shield; 3D-printing; micro-supply chains

1. Introduction

The spread of the coronavirus disease 2019 (COVID-19) has had disastrous consequences on the global economy and healthcare systems, affecting over 100 countries in a matter of weeks [1-5].
Although similar pandemics such as MERS and SARS have occurred in recent decades, increased globalisation, real-time travel, and the ease of transmission have resulted in the rapid propagation of the virus across the globe [3, 6, 7]. Therefore, early preventive measures are necessary to slowdown the infection rate, such as the legal implementation of social distancing protocols and the use of personal protective equipment (PPE) [8-10]. The importance of these measures is further highlighted by recent studies, which report COVID-19 to be transferable similarly to other respiratory viruses, through infectious droplets or by direct contact [11]. PPE is fundamental to slowing the spread of SARS-CoV-2, as it prevents the direct contact of body fluid aerosols from carriers [12, 13]. Such equipment is particularly essential for healthcare workers who risk infection through sprays, splashes, and spatter of body fluids [6, 14]. Face shields are one form of PPE, which offer a protective barrier to control the expelled aerosols of body fluids, protecting both the facial area, and related mucous membranes (eyes, nose, lips etc.) [15, 16]. These simple, transparent screens can be worn alone or in conjunction with other PPE such as masks or respirators, depending on the environment and user occupations [15, 17]. Face shields come in a variety of types and configurations, with the structural components consistent throughout being a visor and a frame. Conventional frames are available in a range of adjustable and nonadjustable sizes, commonly produced from lightweight plastic [17]. Similarly, visors are available in various sizes, which often curve around the face. The face shield must provide good visibility to the wearer while completely covering the sides and length of the face to mitigate the risk of infection [17]. In Europe, face shields are regulated under the European Standard Directives (86/686/EEC, and LS EN 166/2002) to prevent the introduction of defective devices into the marketplace [18]. However, in this midst of the COVID-19 pandemic, many of these standards have been temporarily relaxed as countries face shortages in PPE due to the disruption of traditional supply chains and rapid increases in demand [19, 20].

One potential solution to mitigate shortages is the local fabrication of various PPE to ease pressure until conventional supply chains can recover [21]. Globally, a significant effort was made to rapidly streamline face shield designs and local manufacturing methods, especially in the initial months of the COVID-19 outbreak. Neijhoff et al. presented an updated design of the visor frame for use in 3D printing [22], whereas Celik et al., reported a 3D prototype for single frame visors [23]. Specially modified visors designed for the hospital setting were also widely produced [24]. Barraclough et al. presented a modified visor design to use loupes and a head-light for surgeons to maintain optimal conditions for better results [25]. Concurrently, the maker community, an online group of 3D-printing hobbyists and professionals, iteratively improved upon open-sourced 3D-printed designs and fabrication methods [26]. Several face shield designs were subsequently popularised and manufactured in mass, including the Prusa RC2/3 [27], Verkstan [28], and Precuris [29].

Building on these local fabrication processes and strategies, this article provides a research protocol and the cost implications for the rapid production of face shields using different technologies from the prototyping to distribution stages for individuals, organisations, or local companies with limited resources. The paper outlines a success story of how a team of volunteers manufactured 12,000 face shields over a seven-week period to supply regional shortages in the North-West region of Ireland. All design, manufacturing and distribution processes are described in detail, including testing and prototyping, material selection, clinical feedback, infection control protocols, production output and distribution methods.

2. Materials and Methods

2.1. Initial Concept and Development

The project was initiated on the 26th March 2020 as a result of Ireland’s public health executive (HSE) issuing a request for the development and manufacturing of PPE because of concerns regarding supply chain storages [30]. In response, a group of volunteers from Institute of Technology Sligo (IT Sligo), consisting of scientists, engineers, designers, technicians, electricians, mechanics and
medical consultants formed to investigate solutions and ultimately manufacture PPE to meet the shortage. After an extensive literature search, the team iteratively modified, tested, and obtained clinical feedback on various models to meet the project’s requirements. Numerous design iterations led to a consensus on the 3D-printed model, which was deemed to have an acceptable degree of protection, regulatory adherence, comfort, and use of readily accessible materials. Once the design was tested and approved by the HSE, a manufacturing space was set up in IT Sligo with additional volunteers then mobilised to ramp-up production. Secondary production lines were later established to supply face shields to regional frontline workers other than the HSE. The face shield models produced included a 3D-printed, Flat model and eventually, a Laser-cut model, which were designed to utilise locally available materials and equipment to ease reproduction. Figure 1 illustrates the development of the project from its early stages to full production.

![Figure 1. Timeline of project development.](image)

### 2.2. Production Process

#### 2.2.1. 3D-Printed Model

3D-printing refers to the process of fabricating three-dimensional solid objects through the use of computer-aided design (CAD) to formulate layer-by-layer custom designs [31]. In response to the COVID pandemic, a large online community of 3D-printing hobbyists and professionals formed with the goal of designing, prototyping, and fabricating various PPE equipment (including face shields) to combat the virus outbreak [32, 33]. The openly sourced designs made available by this community allowed anyone with a 3D-printer to begin fabricating face shields locally. By the project’s initiation date, several designs were developed by the community and had already been prototyped, tested and proven successful. Therefore, the team deemed it unnecessary to spend additional time on research and development and instead choose to select a design tested and proven successful by the “Maker” community with further improvements possible once sufficient production had been established. This method allowed for the time required on design and development to be dramatically reduced, enabling for swift production ramp-up. Based on an extensive literature search, the team iteratively modified, tested, and obtained clinical feedback on several open-sourced community designed 3D-printed face shields until ultimately selecting the Verkstan design (Fig. 2) [28]. The added benefit of selecting this design was that the initial failure rate was relatively low as the open-source design had already been tested and optimised. The printing material used included both polyethylene terephthalate glycol (PETG) and polylactic acid (PLA) as they proved the best fit based on local availability, ease of use, cost, and material characteristics.
The 3D-printed model consisted of two components [17, 28, 32]; (i) a forehead band (5 mm thick, 158 mm wide, 181 mm long) made of PETG (PETG 2.85mm, manufactured by Filamentive) or PLA (1.75 mm/2.85 mm RS PRO), and (ii) a transparent visor sheet (A4 document cover, 250 microns) made of clear polyvinyl chloride (PVC) material (unknown manufacturer, donated). The team used seven 3D printers to manufacture the forehead bands including an Ultimaker 2, Ultimaker 2+, Anycube and Creality CR-10s. The settings of the printers were adjusted using Cura (a 3D printer slicing application) to reduce print time while maintaining model functionality. The parameters of each of the 3D-printers vary marginally as can be seen in Table 1. Variations could also be seen between the use of PETG and PLA material, where the PETG had a build temperature of 70°C and print temperature of 240°C, in comparison to PLA, which had a build temperature of 50°C and print temperature of 200°C. All face shields that were 3D printed using PETG material, were cleaned using a wet sponge, and a mixture of bleach and water to remove excess slag. The transparent visor sheet was then secured by pushing the pegs on the forehead band through the 5mm round holes on the transparent visor. Supplementary Material 1 provides a detailed step-by-step overview of the manufacturing and assembly process used for the 3D-printed model.

Table 1. Settings utilised for each 3D printer

| Parameter                | Ultimaker 2 | Ultimaker 2+ | Anycube | Creality CR-10s |
|--------------------------|-------------|--------------|---------|-----------------|
| Nozzle diameter          | 0.4 mm      | 0.4 mm       | 0.4 mm  | 0.4 mm          |
| Line width               | 0.5 mm      | 0.5 mm       | 0.4 mm  | 0.4 mm          |
| Wall line width          | 0.5 mm      | 0.5 mm       | 0.4 mm  | 0.4 mm          |
| Wall line height         | 0.25 mm     | 0.25 mm      | 0.25 mm | 0.25 mm         |
| Layer height             | 0.25 mm     | 0.25 mm      | 0.25 mm | 0.25 mm         |
| Print speed              | 45 mm/s     | 60 mm/s      | 50 mm/s | 50 mm/s         |
| Cooling                  | 100%        | 100%         | 100%    | 100%            |
| Wall line count          | 2           | 6            | 6       | 2               |
| Number of models per print| 2           | 2            | 1       | 3               |
| Infill                   | 40%         | 20%          | 25%     | N/A             |
| Support                  | None        | None         | None    | None            |
| Base plate               | None        | None         | None    | None            |
| Adhesion                 | None        | None         | None    | None            |
| Number of models per print| 2           | 2            | 1       | 3               |
| Infill                   | 40%         | 20%          | 25%     | N/A             |
2.2.2. Flat Model

Once the 3D-printed model face shields design was finalised and production streamlined, the operators began iterative testing and prototyping of new and original designs with the goal of reducing complexity and improving production rates. This research and development ultimately led to the newly designed Flat model face shield, which was driven by the need to increase the production output as the available 3D printers had reached full capacity (Fig. 3). In comparison to the 3D-printed model, the design of the Flat model had much greater simplicity and ease of reproduction by a workforce with limited manufacturing expertise and experience. The model went through several design iterations, which were tested and improved upon until an acceptable fit was found. Unlike many open-sourced designs, the model avoids the need for adhesives to secure the device. This is achieved by having the transparent visor being tightly held in place between the inner and outer visor bands. The Flat model is comprised of five components: (i) a transparent visor sheet (A4 document cover, 250 microns) fabricated from transparent PVC material (unknown manufacturer, donated), (ii) an outer visor band (0.1 mm thick, 22 mm wide, 364 mm long) formed of Acrylonitrile butadiene styrene (ABS) plastic, (iii) an inner visor band (0.1 mm thick, 22 mm wide, 360 mm long) made of ABS plastic (unknown manufacturer, donated), (iv) a forehead band (0.1 mm thick, 22 mm wide, 300 mm long) made of ABS plastic (unknown manufacturer, donated), and (v) a back strap (10 mm to 20 mm wide, 250 mm long) made of elastic fabric (unknown manufacturer, donated). Supplementary Material 2 provides a systematic overview of the steps necessary for the manufacturing and assembly of items (ii), (iii), (iv), and (v), describing how the components are cut to size and then stapled in place. The transparent visor sheet is then slid between the inner and outer visor bands where it is held in place.

Figure 3. A prototype of the Flat model face shield.

2.2.3. Laser-Cut Model

In an effort to improve efficiency and production output, a new design was prototyped and manufactured named the Laser-cut model. This design was conceptualised after a large roll of polyethylene terephthalate (PET) material was donated to the project, which was compatible with an in-house laser cutter (Mantech Laserteck 90130) shown in Fig. 4. The processing parameters of this laser cutter included a speed of 200mm/s, max power 97.6%, a bed size of 900x1300mm, and an 80W water DC cooled laser tube. The Laser-cut model design was based heavily on the Flat model with the main alteration being to the material used, replacing the ABS visor and forehead bands with PET. Thus, providing a cost-effective, durable, and lightweight alternative, while exploiting underutilised
local supply routes. The Laser-cut model produced comprises of three components; (i) a forehead visor (0.1 mm thick, 210 mm wide, 385 mm long) fabricated from PET plastic (Xtrupak), (ii) a forehead band (0.1 mm thick, 52 mm wide, 324 mm long) made of PET plastic (Xtrupak), and (iii) a back strap (10 mm to 20 mm wide, 250 mm long) made of elastic fabric (unknown manufacturer, donated). Supplementary Material 3 provides the design specifications for the forehead visor and the forehead band, which were cut in bulk using a laser cutter. This dramatically simplified and reduced production time by incorporating the visor and visor band into a single laser-cut component. Supplementary Material 4 provides a systematic outline of the manufacturing and assembly process.

**Figure 4.** Pictures of (a) Laser cutter set-up; (b) Prototype of Laser-cut model.

### 2.3. Design Guidelines and Infection Control Protocols

In Europe, face shields are regulated under the European Standard Directives 86/686/EEC and I.S.EN 166/2002 with similar policies in place in other countries [34, 35]. A major difficulty at the beginning of the project was that there was no clear pathway for the introduction of unapproved and locally fabricated medical face shields into the Irish clinical setting.

To overcome this potential issue, the HSE provided condensed guidelines following the IS EN 166 technical standards [36]. These guidelines provided recommendations regarding general construction, materials, headbands, the field of vision, optical requirements, protection against droplets and splashes of liquids, and resistance to fogging. Once production commenced, the face shields were regularly inspected to ensure the production quality was upheld. These tests included regular functionality testing and visual inspections to ensure each component was free from defects, cracks, or crevices. Additionally, the production line was inspected by the HSE Infection Control team to ensure the manufacturing and distribution process followed the recommended guidelines and to provide suggestions for further improvement.

A significant concern for the project was the risk of a team member unknowingly catching and transmitting the COVID-19 virus during the production and assembly process. To mitigate this threat, the team conducted a risk assessment, established protocols, and followed HSE guidelines (EN 166) [36]. These guidelines included the regular sanitisation of equipment and hands with a solution of 70% ethanol/isopropyl alcohol (purchased from Sigma-Aldrich Merck), and all volunteers wearing PPE, including gloves and facemask, to minimise the potential for viral infection or device contamination. Other measures included attempting to follow social distancing guidelines by keeping volunteers on the same shifts and storing all face shields according to their day of production.
For added protection, various sterilisation processes were considered. Prior to assembly, all raw materials were wiped down with a solution of 70% ethanol/isopropyl alcohol. Two further sterilisation options were considered for face shields post-assembly. The effectiveness of a heat treatment decontamination process was tested, which involved the face shields placed in an oven kept at 70°C for 30 minutes (ramp-up 5°C/minute). An alternative sterilisation process that was also considered, was dipping the devices into a solution of 1% sodium hypochlorite and water for a minimum of 10 minutes [37]. After communicating with relevant experts, this step was later skipped, as the advisors were satisfied that the risk of COVID contamination was adequately addressed through the use of PPE and sterilisation of raw materials prior to assembly.

3. Results

3.1. Project Development and Output

The production line operated five days a week on two shifts per day (four hours each) with its development illustrated in Fig. 5. The team involved grew proportionally to the project’s expansion, with fifty-five volunteers overall and six volunteers typically working per shift. The project was coordinated through bi-weekly management meetings between senior team members. Over the timeframe of the project, a total of 12,000 face shields were produced with the ramp-up of production. At full production (11th – 22nd May 2020), 353 face shields were manufactured a day on average, 18% 3D-printed models, 50% Flat models, and 32% Laser-cut models.

To distribute the face shields, regional businesses and organisations which were deemed vulnerable were contacted by phone. If the company or organisation expressed a need, a quantity was agreed, and the delivery method arranged. On delivery, the face shields were sealed within plastic packaging to minimise the potential for contamination. Each delivery-included essential information about the devices, including their fit for purpose, testing, approval, and recommended processes for disposal and sterilisation (included in Supplementary Material 5). The distribution of the face shields to the HSE (38%) followed by the Sligo County Council (9%), and the ambulance services (7%). The remaining face shields were distributed to secondary channels including Garda Síochána (Irish police), general practitioners, civil defence, hospitals, nursing homes, pharmacies, medical centres, and other frontline services.

Figure 5. Daily productivity of face shields.

3.2. Comparison of Face Shield Models
Over the project, three face shield models were developed and produced, namely the Flat, Laser-cut, and 3D-printed models. Each of the models differed in their production process but maintained the same high level of protection for the end-user. A comparison of the face shields models is presented in Table 1. Although the production rate of the 3D-printed model remained relatively constant, the Flat model and Laser-cut model varied heavily depending upon the volunteers’ skill and experience, with the units produced varying from 30 to 150 units/day. Additionally, the training necessary for the Flat and Laser-cut models was relatively quick, typically consisting of a quick demonstration lasting 5 to 10 minutes. In contrast, the 3D-printed model took significantly more time before the volunteer felt capable (typically 2 to 4 hours).

Considerable differences were seen in the failure rates between face shields, as shown in Table 2. The failure rates of the Flat model were the most variable, as it was highly dependent on the skill and experience of the operator. Operators on their first shift experienced the highest device failures (up to 40%) with this diminishing quickly over time, as the operator gained experience. An advantage of the Flat model was that defective models were easily repaired, resulting in little to no waste. The Laser-cut model experienced the lowest rates of failure with the laser-cutter (Mantech Laserteck 90130) proving particularly effective combined with the devices simplistic design, allowing for easy assembly. Finally, the 3D-printed model experienced a failure rate of approximately 5% with defective devices typically being discarded as they could not be repaired.

Table 2. Comparison of face shield models.

| Features                           | 3D-printed Model | Flat Model | Laser-cut Model |
|------------------------------------|------------------|------------|-----------------|
| Components                         | - Forehead band  | - Forehead visor | - Forehead visor |
|                                    | - Transparent visor | - Visor Band inner | - Forehead visor |
|                                    |                   | - Visor Band outer | - Visor visor |
|                                    |                   | - Visor sheet | - Elastic strap |
|                                    |                   | - Back strap | |
| Adherence to IS EN 166 technical standards | ✓              | ✓           | ✓               |
| Tested by HSE                      | ✓                | ✓           | X               |
| Final two-week avg. production rate (units/day) | 90       | 227         | 245             |
| Approx. failure rate               | 5%               | 7%          | 1%              |
| Adjustability for head size        | All sizes        | Small to medium | Medium to large |
| Energy consumption (kWh/face shield) | 0.166           | N/A         | 0.0004          |
| Training required                  | - Experienced personnel required to operate printers | - Little training needed | - Experienced personnel required to operate laser-cutter |
| Advantages                         | - Easy to sterilise (PETG material) | - Little waste as failures can typically be reworked | - High production rate |
|                                    | - Long production time | - Simplistic design | - Simplistic design |
|                                    | - High failure rate | - Heavy dependent on operator skill and experience | - Lightweight material |

The face shield models varied significantly in terms of production costs, as shown in Table 2. These figures present the expenditures in raw materials for each face shield model and the associated equipment costs. Note that equipment expenditures were not incurred in this project as they were provided in-house. Therefore, the costs presented are based on quotations gained. When considering the cost of raw materials only, the Laser-cut model proved to be the most cost-effective for the production of the face shield. While the Flat model showed to be the most economical overall, it is
anticipated if the project was to continue the costs associated with the Laser-cutter model would reduce dramatically. Moreover, feedback gained from the end-users showed little differences stated between the model’s features (e.g. reliability, comfort). Therefore, it is recommended that individuals or teams attempting to replicate this case study prioritise the Flat model if using basic equipment and the Laser-cut model if manufacturing at scale.

**Table 3. Breakdown of project expenditures**

| Material                  | Unit     | Cost/unit (incl. Vat) | Face shield/unit | Cost/face shield |
|---------------------------|----------|-----------------------|------------------|------------------|
| **Flat Model**            |          |                       |                  |                  |
| **Raw Materials**         |          |                       |                  |                  |
| ABS plastic roll (0.1mm, thick, 100m x 22mm) | Roll     | €24.60                | 92               | €0.27            |
| A4 PVC document (250 microns) | Pack     | €20.00                | 100              | €0.20            |
| Elastic fabric            | Pack     | €0.12                 | 4                | €0.03            |
| Staples 12 mm – pack of 400 | m        | €7.50                 | 2,000            | €0.00            |
| **Equipment**             |          |                       |                  |                  |
| Heavy duty stapler        | 2        | €70.00                | 5,950            | €0.01            |
| Scissors                  | 5        | €10.00                | 5,950            | €0.00            |
| **Average cost per unit** |          |                       |                  | €0.51            |
| **3D-printed Model**      |          |                       |                  |                  |
| **Raw Materials**         |          |                       |                  |                  |
| 3D printer filament       | Roll     | €27.00                | 33               | €0.82            |
| A4 PVC document cover (250 microns) | Pack     | €20.00                | 100              | €0.20            |
| Elastic Fabric            | m        | €0.12                 | 4                | €0.03            |
| **Equipment**             |          |                       |                  |                  |
| Ultimaker 2               | 7        | €2,502.20             | 2,174            | €8.06            |
| **Average cost per unit** |          |                       |                  | $9.10            |
| **Laser-cut Model**       |          |                       |                  |                  |
| **Raw Materials**         |          |                       |                  |                  |
| Large roll of PET         | Roll     | €580                  | 3,876            | €0.15            |
| Elastic Fabric            | Pack     | €20.00                | 100              | €0.20            |
| **Equipment**             |          |                       |                  |                  |
| Mantech Laserteck 90130   | 1        | €7,927.36             | 3,876            | €2.05            |
| **Average cost per unit** |          |                       |                  | €2.40            |

* Direct quotation provided from supplied of Ultimaker [38]; † Direct quotation provided from by Mantech [39].

4. Discussion

Given the circumstances brought upon by the COVID-19 pandemic and the subsequent shortages in PPE, the study proposed a protocol for the design and rapid production of face shields for infection control. The case study demonstrated that a team of volunteers with limited tools operating in a conventional office environment could meet the regional demand for medical face shields. Over the seven weeks understudy, a total of 12,000 face shields were produced and distributed, averaging 353 units/day. In this time, production was gradually optimised using various methodologies, such as (i) improved forecasting of supply and demand (ii) standardising inventory management and procedures (iii) improving onboarding process and (iv) communication of plans to team.

The team engaged heavily with known experts and frontline users to gather feedback regarding the design of the device. Generally, the feedback was provided through follow-up interviews (calls)
and emails, where each of the organisations and companies supplied (totaling 94) were contacted by a senior member asking if they required a reorder, satisfied with the devices provided, and for suggestions for improvement. The responses received were overwhelmingly positive with users stating that the devices were comfortable, reliable, and durable. The Flat model and Laser-cut model face shields, in particular, were able to accommodate the vast majority of users due to their elastic back strap. The appropriate size of this back strap was determined in the projects development stages by trailing the face shields on several test users. However, the team did consider that they might be outliers, so added a small percentage of face shields with a larger back strap to each batch.

Although the devices do not meet regulatory standards i.e. CE or Food and Drug Administration (FDA) approval, they do act as an emergency alternative capable of supplying local demand during exceptional circumstances. The devices have been rigorously tested by the Institute of Technology Sligo and the approved for use by the HSE and Sligo University Hospital Clinical Infection Team. Therefore, the authors propose that given the current circumstances, the risk of using the device is small compared to the risk of COVID-19 transmission. Furthermore, an inspection of the production hub by the HSE and subsequent feedback proved valuable. Recommendations included an alteration to the Flat model fabrication process to improve reliability and a preference to produce the 3D-printed face shields using PETG material as it offered improved disinfection with minimum damage during sterilization [40].

Based on existing face shields published in the literature, the production time of the 3D-printed face shield and its cost of materials and equipment was comparable to other designs available [41]. For individuals or teams aiming to replicate the production of the 3D-printed model, it is recommended that both a larger nozzle and layer be utilised (0.8 mm-1.2 mm) to maximise the production rates. Additionally, it is recommended that a thermal insulator (Mosquito Magnum) is used to protect the extended melt zone from the active cooling effects and radiative heat loss (heat transmission rate: 3W/m*K) [42]. Moreover, a E3D Super volcano accessory could be added to facilitate faster printing time, reduce breakages, and improve the material properties [43].

The team halted the production of the face shields on the 22nd May 2020 as regional supply chains had recovered from the initial disruption. However, the team had established measures to resume production if it becomes necessary. In the event of another health crisis, where face shields needed to be produced on mass, the team would make the following recommendations:

- The Flat model proved to fill a considerable gap as an effective face shield requiring little equipment, no adhesives, cost-effective with a simplistic manufacturing process [44, 45]. Unlike the other designs, production at scale can be quickly established and should be considered as a first response design if a similar health care crisis were to take place. Furthermore, in comparison to other visors commercially available in the market, the Flat model showed a significant cost reduction of up to 50% [46].

- A major difficulty for the project was the sourcing of raw materials with changes in production and modifications in face shield design needed to overcome the shortages. The use of social media and existing contacts proved useful in overcoming such difficulties [47].

It should be noted that the material selection for the face shield models was greatly influenced by the availability of local supplies within the North-West region of Ireland. Therefore, individuals or teams aiming to replicate this case study should modify the design to exploit underused supply routes available in their region.

5. Conclusions

This study presents a research protocol for the rapid development and manufacturing of face shields by individuals or companies with minimal resources. The paper describes the success story of the swift production of 12,000 face shields over a seven-week period to meet PPE shortages in the North-West region of Ireland. Over the project, three face shields designs were prototyped, manufactured and eventually distributed to frontline services; namely the Flat, Laser-cut, and 3D-printed models. The Flat model proved to be the most cost-effective (€0.51/unit), while the Laser-cut model was the most productive (245 units/day). The project has since halted production as regional
supply chains have recovered but have established measures to resume if shortages in PPE re-emerge. The broader implications of this work highlight the ability of a voluntary workforce to be rapidly mobilised to fabricate emergency equipment during a time of crisis, such as the COVID-19 pandemic. Going forward, the authors recommend that policymakers and healthcare personnel consider this capability when planning for the next potential health care emergency.

**Supplementary Materials:** The following are available online, Supplementary Material 1: Instructions for the production and assembling of the 3D-printed model face shield, Supplementary Material 2: Production and assembling guide for the Flat model face shield, Supplementary Material 3: Design specification for the Laser-cut model face shield, Supplementary Material 4: Instructions for the production and assembling of the Laser-cut face shield, Supplementary Material 5: Essential information included with each delivery.

**Author Contributions:** Conceptualisation, S.O.C., S.M., and S.C.P.; designed face shield models, M.G., R.M., and P.M.N.; set-up and managed the production lines, M.G., P.M.N., U.P.; S.C.P., J.B., D.T., R.M.M, and R.M.; writing—original draft preparation, S.O.C., S.M., and F.D.; analysed the data, S.O.C., M.G., and P.M.N.; prepared figures, S.O.C., and P.M.N.; writing—review and editing, S.O.C., S.C.P., S.M., F.D., D.T., U.P., and J.B., supervision, S.C.P., U.P., D.T and J.B. All authors reviewed the manuscript.

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**Highlights**

- Explores alternative supply routes for the manufacturing and distribution of medical face shields with minimum equipment and materials
- Of the models tested, the Laser-cut model proved the most cost effective (€0.35/unit) and productive (245 units/day) with no apparent drawbacks
- Local voluntary workforces can be mobilised to quickly meet personal protective equipment (PPE) shortages in response to a health care emergency
Author Contributions: Conceptualisation, S.O'C., S.M., and S.C.P.; designed face shield models, M.G., R.M., and P.M.N.; set-up and managed the production lines, M.G., P.M.N., U.P.; S.C.P., J.B., D.T., R.M.M, and R.M.; writing—original draft preparation, S.O'C., S.M., and F.D.; analysed the data, S.O'C., M.G., and P.M.N.; prepared figures, S.O'C., and P.M.N.; writing—review and editing, S.O'C., S.C.P., S.M., F.D., D.T., U.P., and J.B., supervision, S.C.P., U.P., D.T and J.B.. All authors reviewed the manuscript.

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