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Fast mass-production of medical safety shields under COVID-19 quarantine: optimizing the use of University fabrication facilities and volunteer labor

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ABSTRACT

COVID-19 pandemic provoked a number of restrictive measures, such as the closure or severe restriction of border transit for international trading traffic, quarantines and self-isolation. This caused a series of interrelated consequences that not only prevent or slow down the spread of disease, but also impact the medical systems' capability to treat the patients and help their recovery. In particular, steeply growing demand for medical safety goods cannot be satisfied by regular suppliers due to the shortage of raw materials originating from other countries or remotely located national sources, under conditions of quarantined manpower. The current context inevitably brings back memories (and records!) of the situation 80 years ago, when WWII necessitated major effort directed at the rapid build-up of low cost mass production to satisfy all aspects of war-time need. In the present short report we document a successful case of fast mass-production of light transparent medical safety face shields (thousands per day) realized in Skolkovo Institute of Science and Technology (Skoltech) fabrication laboratory (FabLab). The demand for safety face shields by tens of hospitals in Moscow City and Region rapidly ramped up due to the need to protect medical staff during patient collection and transportation to hospitals, and within both the infected ("red") and uninfected ("green") zones. Materials selection for sterilizable transparent materials was conducted based on the analysis of merit indices, namely, minimal weight at given stiffness and minimal cost at given stiffness. Due to the need for permanent wear, design was motivated by low weight and comfortable head fixation, along with high production efficiency. The selection of minimal tooling in University fabrication workshops and the use of distributed volunteer labor are discussed.

Keywords: personal protection equipment, COVID-19, mass production

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INTRODUCTION

Extraordinary circumstances of COVID-19 pandemic significantly change the landscape in many fields of businesses, activities and everyday life. New challenges emerged in the production, supply and trading of many goods such as personal safety means and protection wear which are directly affecting the capabilities of hospitals to limit the spread of infection between medical personnel and, therefore, currently extra demanded. The efficiency of goods like face filtering masks and transparent full face medical shields is discussed and impugned by some specialists [1]. It is clear, however, that even imperfect extra protection reduces the risk for medical personnel in hospitals, paramedical personnel and volunteers, and ultimately for the ordinary citizens.

Although open transparent full face medical shields (Figure 1) are undoubtedly less efficient than hermetic face masks protecting eyes and nose, the emergency demand for these is estimated at millions of pieces worldwide and needs to be answered within a matter of weeks. Stock reserves of medical shields are limited and many ready mask substitutes from sport (for divers and cyclists) or professional use (for stonemasons, woodworkers and metalworkers) are being used up, although their stock reserves are also relatively low.

Meanwhile, stringent border controls over international trading traffic introduced by many governments in combination with obvious logistic limitations prevent fast supply from traditionally low cost sources (China, Indonesia) with industrial infrastructure for mass-production for global demand built up over decades. The current context conjures up memories of World War II context when all available national manufacturing resources and manpower were mobilized for low cost mass production. Low cost mass fabrication practices from that epoch may turn out to be relevant, with obvious adaptation to the modern technological, communication and logistic landscape.

Current pandemic situation and quarantine limitations are posing a number of challenges distinct from the circumstances of the XX century World Wars. The following aspects need to be taken into account:

- Big cities which are the most affected by COVID-19, such as Milan, Madrid, London, New York and Moscow. These are deeply deindustrialized, while external supplies of raw materials and tools are subject to delays or entirely disrupted.
- Manpower is mainly quarantined (self-isolated) or has limited access to production workshops.
- Nevertheless, some stock reserves of raw materials remain readily available in local manufacturing plants and transit warehouses or at least in commercial centers, such as OBI, Leroy Merlin, Petrovich, or similar.

- As a universal rule, big cities are also centers of academic science concentrated in universities. Materials Science and Engineering Departments support fabrication centers and laboratories equipped with traditional and modern tools for shaping metal, polymer and composite materials.
- CAD/CAM production paradigm suggests that a small number of designers (quarantined at home) and workers (granted access to workshops and focused on performing the most complex fabrication operations) can generate a significant volume of simple parts for further manual assembly by a community of volunteers or users on or off site.
- The transportation and delivery of parts and the collection of assembled ready products can be organized via automated delivery.

We document a successful case of fast mass-production (*thousands of items per day*) of light transparent medical safety face shields realized in Skoltech's fabrication laboratory (FabLab). These safety face shields were in peak demand by tens of hospitals in Moscow City and Region to protect medical staff in both infected ("red") and clean ("green") zones. Ashby's materials selection algorithm [2] was applied in respect of sterilizable transparent material to satisfy the performance indices for minimal weight at given stiffness and minimal cost at given stiffness.

By the application of "as simple as possible" design principle to medical face shields, production was devised to use small and medium scale laser cutters widely available in university workshops and fabrication laboratories. The design was targeted to enable permanent wear of this means of protection, via the reduction of weight and providing comfortable fixation to head. Aspects of minimal tooling and the use of "assembling by final user" or "distributed volunteer labor" and sterilization are discussed.

REQUIREMENTS AND CONSTRAINTS.

The well-known prototype of the designed product is exemplified in Figure 1(a). COVID-19 full face shield protects the wearer's eye mucous lining from direct flow of infected aerosol, while nose and mouse should benefit from the additional defense by tissue face mask, on the assumption that viral aerosol cannot penetrate the skin barrier, so that only mucosa are at risk. A readily affordable substitute, such as one of the variants of construction workers' protection mask (Figure 1b), as well as professional medical goggles defend both against direct flow of infected matter from patient and the suspended aerosol most important in closed rooms of "dirty" (red) zones in hospitals. Goggles worn for many hours cause skin compression, scratching and irritation at the nasal bridge, upper cheeks and

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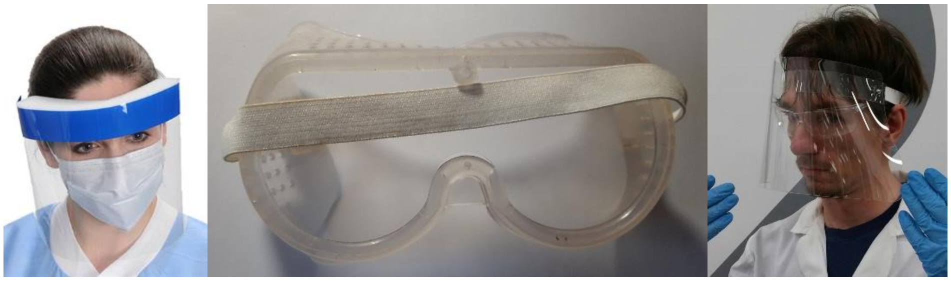
forehead, thus creating locations with increased potential risk of infection. This poses a difficult choice for medical personnel and hospital management in the selection of the best type of personal protection equipment (PPE). Nevertheless, it appears that manipulations carried out with patients in open spaces during evacuation to hospital or disinfection operations can be safely performed using full face shields. Below we discuss the design, materials selection, technology and production efficiency of the full face shield devised in FabLab of Skoltech (Figure 1c and Supplementary Materials).



a **B** **c**

Figure 1. Example of personal protection equipment: a) full face shield (Medical Supplies and Equipment Co., Katy, Texas 77450, USA) b) construction worker goggles Archimedes 91862 (Technoplast Ltd., St. Petersburg, Russia) c) full face shield (FabLab, Skolkovo Institute of Science and Technology, Moscow, Russia)

The price of professional industrially manufactured full face shield reaches tens of USD and lead time of several weeks not acceptable during pandemic. Relatively cheap (units of USD) and easily affordable protection mask (exemplified in Figure 1b) made from polycarbonate glass are designed for the protection against impact of metal and stone debris, making it heavier, while their optical characteristics do not satisfy the end user requirements in the medical context, since the clarity and transparency for fine hand operations are modest. The weight of commercially available products may reach 380 ± 80g.

The total weight of the devised full face shield met the overall objective of 36±3 g and 56±3 g in different versions, depending on the shield dimensions. Thus, it is much lighter than the industrial analogues available on the market. The weight of the full face shield must be accounted for in the context of head movement by personnel, since it needs to be balanced by the distributed force of the forehead strip, fastening elastic band and fasteners, and ultimately transmitted through neck muscles. Head and shoulder loading from the lighter face shield is several times lower for the devised product than for its industrial analogues.

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MATERIALS SELECTION

Materials selection for a transparent medical face shield represents a relatively simple problem in the context of Ashby materials selection paradigm, as implemented in the educational CES Edu Pack 2019 software [3]. Systematic procedure requires the following steps: i) translation of design requirements, ii) screening against the material attribute limits, iii) ranking of materials in terms of performance indices; and iv) expert assessment and local testing. This was carried out as follows:

i) Translation

Function: Stiff panel (plate) resisting the bending force

Objective: a) Minimize mass; b) Minimize cost

Constraints: *Non-negotiable constraints*: * transparency: transparent or optical quality * non-alergic and non-toxic in the contact with skin *Area AxB is specified * must not be brittle

Negotiable constraints: * must withstand limited bending force with small distortions * must not yield, buckle or failure under own weight and limited bending force

Free variables: ***** plate thickness * material choice

ii) Screening

The constraint on transparency significantly reduces the number of candidates – from more than 4000 down to 197 as shown in the Figure 2 a). The candidates passed “transparency” filter represent different classes of materials (Figure 2b) including senseless fibers and particulates and technical ceramics like saphires and quartz and various glasses. Ceramics and glasses will be further excluded because of brittleness and obvious technological difficulties in application of shaping processes. The limitation on material class (polymers and elastomers are passing this filter) further cuts down the number of candidates (Figure 2c) – only 130 materials are considered at the ranking stage.

iii) Ranking

The performance indices relevant for mininal mass $\frac{\rho}{E_f^{\frac{1}{3}}}$ and cost $\frac{C_m \cdot \rho}{E_f^{\frac{1}{3}}}$ of bent panel were chosen as the axes for Ashby chart (Figure 3a). Here ρ is density, E_f is flexural modulus and C_m is the price per unit mass. Left bottom corner is the region of interest corresponding to light cheap material solutions and the sample of 16 candidates that

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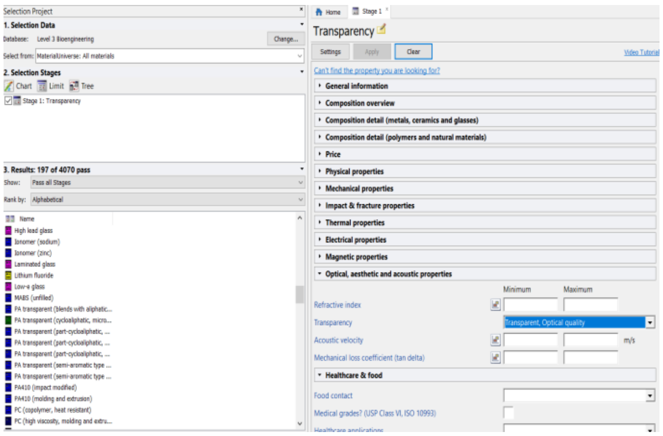
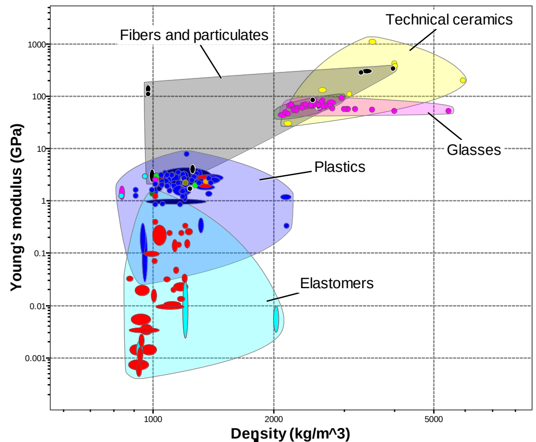
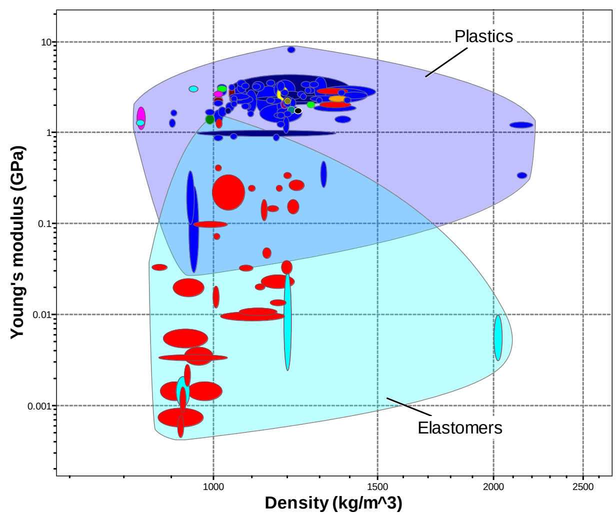
region is depicted in the Figure 3 b. Red dash line represent the envelope for best weight (SAN) and cost (SMMA) solutions.



a



b



c)

Figure 2. Materials selection for transparent medical face masks. Screening stage: a) the list of candidate materials passed "transparency" filter; b) Ashby charts for all transparent materials and c) for polymers and elastomers (Charts and data from CES EduPack 2019, Granta Design Limited, Cambridge, UK, 2019 [3]).

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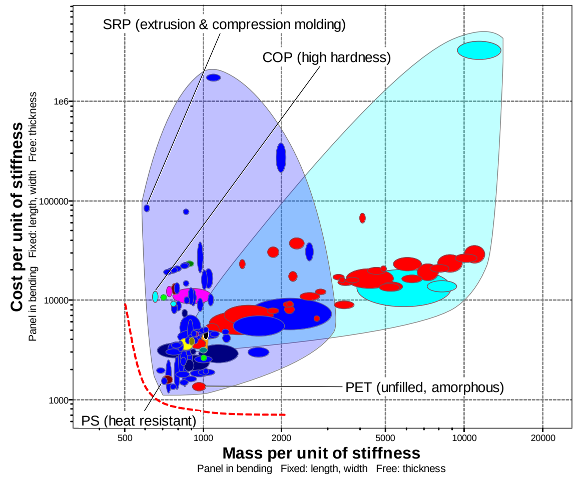
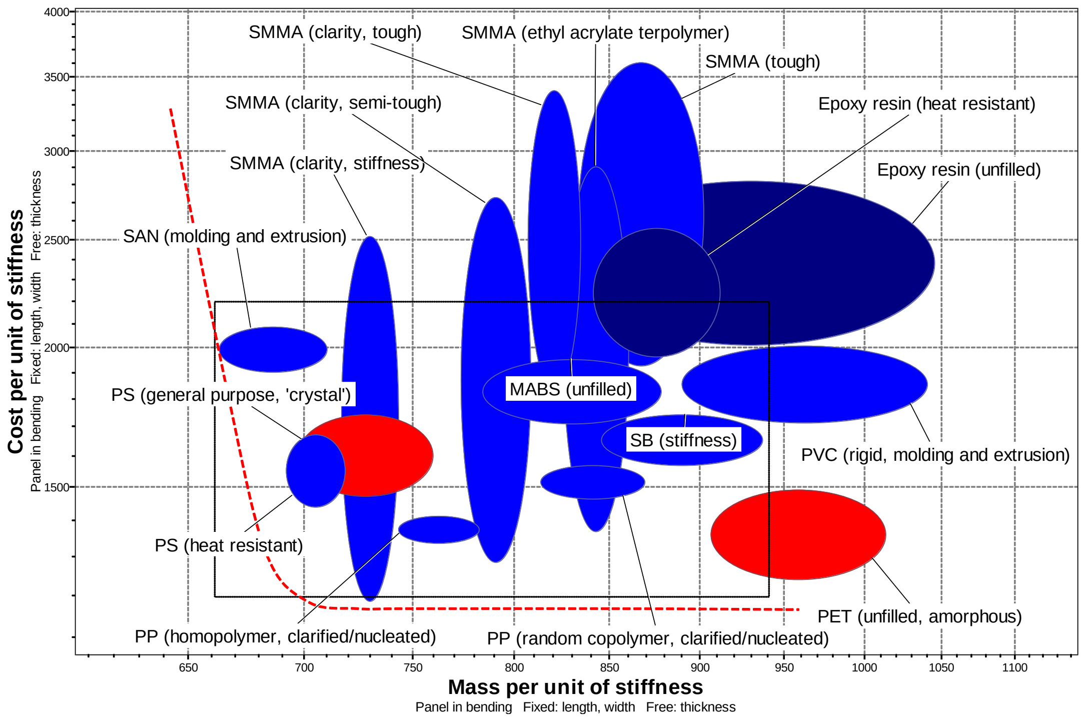


a)



b)

Figure 3. Materials selection for transparent medical face masks. Ranking stage: a) 130 candidates; b) 16 candidates (red - optical quality; blue – transparent). (Charts and data from CES EduPack 2019, Granta Design Limited, Cambridge, UK, 2019 [3])

iv) Expertize and testing

The list of the most attractive candidates is given below in the Table 1 in the order of asscending value of cost per unit stiffness. Four candidates namely SMMA, PET, SAN and PS are durable in water and weak organic solvents, acids and alkalis, readily sterilizable (except autoclave) and appropriate for the use in contact with human skin and they seem to be the most recommended while the final choice is to be defined after the analysis of local prices, stock resources and available equipment for fast shaping. The PET of optical quality (that is an extra benefit) in ready sheets having thickness 0.5 mm and 0.3 mm for shortened "S" version has been finally chosen due to the fact that it was the most affordable for the Skoltech's Fablab in March and April, 2020. This material scores second place in respect of cost saving, being, however, at least for 30 % less attractive in respect of weight than polystyrene.

Table 1

Performance of candidate materials (two top candidates in respect of each performance indices are highlighted in grey) (Data from CES EduPack 2019, Granta Design Limited, Cambridge, UK, 2019 [3])

N	Name	Cost per unit of stiffness (USD/(GPa$^{1/3}$·m^3))	Mass per unit stiffness (kg/(GPa$^{1/3}$·m^3)) (Place in the order of ascending mass)	Comments
1	Styrene-methyl methacrylate copolymer **SMMA** (clarity, stiffness)	1190 - 2520	716 – 743 (3)	Susceptible for stress whitening
2	Polyethylene Terephthalate **PET** (unfilled, amorphous)	1240 - 1490	907 – 1010 (10)	Not suitable for negative temperatures
3	**SMMA** (clarity, semi-tough)	1290 - 2730	773 – 808 (5)	
4	Polypropylene **PP** (homopolymer, clarified/nucleated)	1340 - 1410	743 – 782 (4)	
5	**SMMA** (ethyl acrylate terpolymer)	1370 - 2910	825 – 859 (8)	
6	Polystyrene **PS** (heat resistant)	1440 - 1670	692 – 718 (2)	Poor wear and fatigue resistance
7	**PP** (random copolymer, clarified/nucleated)	1470 - 1570	814 – 869 (7)	
8	**PS** (general purpose, 'crystal')	1470 - 1740	697 – 759 (3)	
9	Styrene-Butadiene **SB** (stiffness)	1570 - 1740		
10	Methyl methacrylate-acrylonitrile-butadiene-styrene **MABS** (unfilled)	1710 - 1950	784 – 878 (6)	
11	Polyvinyl chloride **PVC** (rigid, molding and extrusion)	1720- 2010	890 – 1040 (9)	
12	Styrene acrylonitrile **SAN** (molding and extrusion)	1910 - 2090	663 – 710 (1)	Poor wear resistance

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PRODUCTION REQUIREMENTS FOR DESIGN.

SHAPING AND ASSEMBLING OPERATION PROTOCOL

The guidelines of low cost mass production listed below are well known but difficult to be universally applied for all products, but it was historically proven in economics of wars that they are efficiently applicable in the situation when the product is relatively simple and commercial issues such as sales and profits are not involved. Nevertheless, high motivation, creativity, labor discipline and strong management are required to reach the desired records of fast low cost mass-production.

The guidelines for fast low cost mass-production are:

A) All designs must be as simple as possible. This means both minimal number of parts and simplest design of each part.

B) All materials applied must be as cheap and as more affordable as possible.

C) All technologies applied must be as simple as possible to achieve the highest productivity relying on simplest tooling for shaping and no tools for assembling and unqualified manpower (any end-user such as oldsters, housewives and teenagers).

D) The number of technological steps, pre- and post- treatments must be minimized. This includes material synthesis, shaping and joining or assembling.

E) The transportation of parts must be minimized along the production chains.

Following these guidelines, the design was based mainly on the cutting of ready sheets of PET and elastic fabric band. The layout of the pattern ready for laser cutting of front flap and forehead strip is represented in the Figure 4. This pattern was used to cut PET lists having 0.5 mm thickness (or 0.3 mm version is 35 mm shorter and 30 mm narrower). This material has been justified in terms of optical quality and minimal cost (although, other candidates provide advantages in terms of minimal mass) above and it is relatively affordable in local conditions. Other materials from the Table 1 are merely suitable if affordable from local suppliers since they also possess adequate rigidity. When changing the material, one needs to experimentally adjust the laser power and cutting speed only. Drawings do not need to be changed, that is an important and obvious advantage.

Fixing back elastic band can be realized from potentially any flat elastic band (preferably with minimal elasticity) or round (Ø 2 to 3 mm) rubber ribbons available in a needlework and sewing store. A flat elastic fabric band 20 mm was used in the particular design to adjust the length of band for optimal personal comfort.

A variant that does not require riveting (only 3 part are needed) is presented in the Supplementary Materials.

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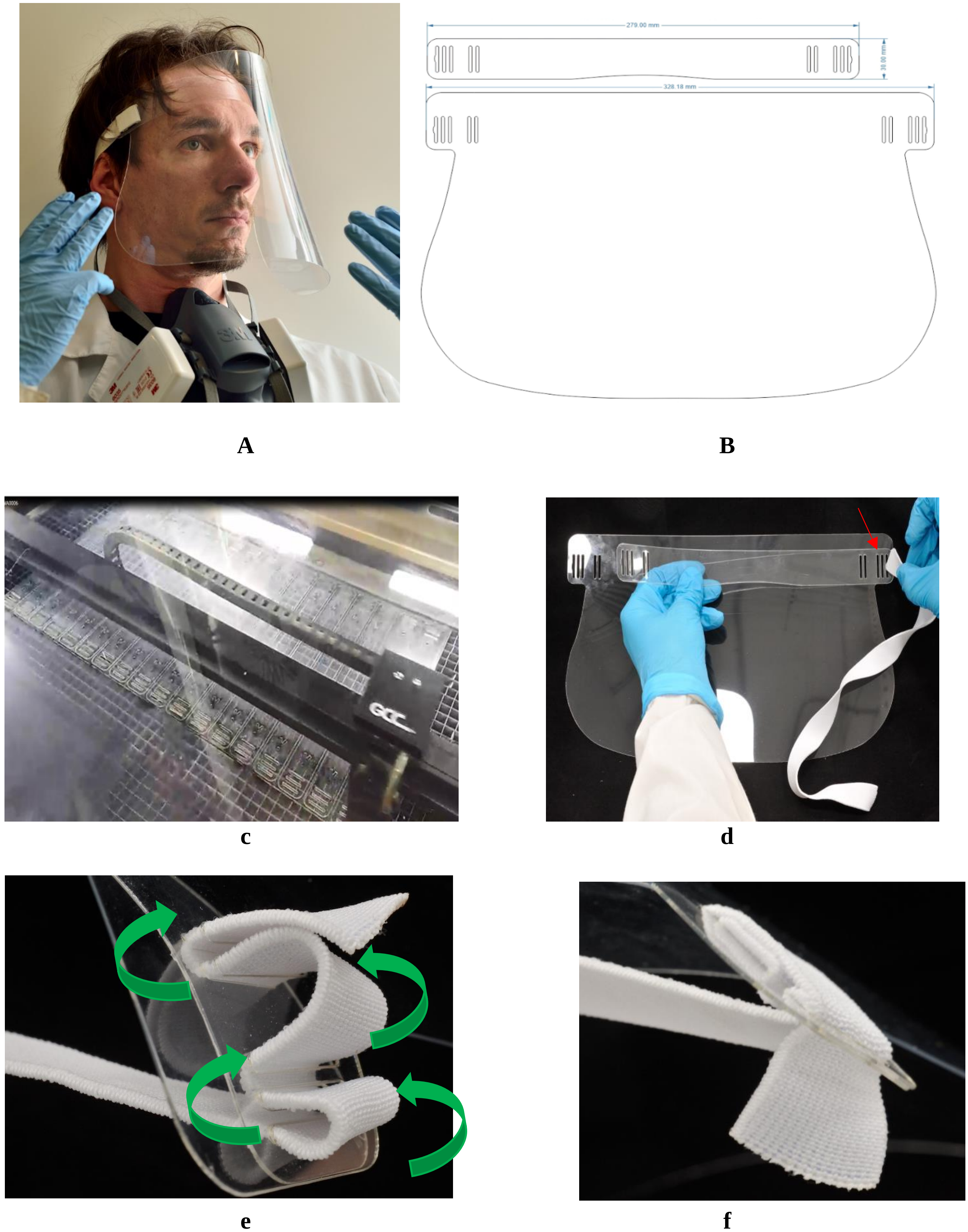

Figure 4. Devised full face transparent shield – stages of fabrication a) ready product; b) pattern for laser cutting; c) laser cutting of forehead strip; d), e) assembling of forehead strip and front flap together with fabric elastic band; f) the adjustment of band length to maintain comfort pressure

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TOOLS AND PARTS.

In the 21st century, public workshops, fabrication departments, laboratories or workshop facilities in the universities, at schools and in creativity clubs for children and youth became widely spread. Almost all of them have CAD/CAM equipment such as 3D printers and, what is the necessary for this particular design - a laser plastic cutter with suitable working characteristics. On the other hand, an option of cutting with a hot knife requires minimal training (less than 5 minutes), but is accompanied by the need for intensive exhaust ventilation. That is hardly to implement at home in a city, but it is still a reasonable manner outside or in countryside workshop in warm climate with the personnel having breath protection means.

The minimal set of equipment includes:

- a laser cutter[1] (available in a huge number of workshops) of any power, though the mastered regime suggests that optimal performance is achieved at 100 W on PET;
- a soldering iron as a hot knife.

Equipment and recommendations for the production:

1. Cutting the sheet material for the front flap and forehead strip.

- A CO2 laser cutter with any characteristics. If the maximum performance is required, it is optimal to use a nominally 100 W laser and an average speed of 105±10 mm/s (depending on actual layout of cut part within the sheet area) at 70% of power to avoid laser source degradation. A SYNRAD FSTI100SFB, 48.3V/21A laser tube was used in the present case. If the laser cutter can maintain the quality of curved surfaces at a higher speed and the laser lifetime can be consumed, it is advisable to increase both characteristics up to the limit to be experimentally found.

  One should expect a production rate of about 6 cut parts per 4min 30sec at 900x600mm at each laser cutter. One person can operate two laser cutters simultaneously which results in up to 130 sets in an hour (fume-extraction time is added). Smaller machine will decrease the productivity. *Mechanical pattern cutters driven by pneumatic, hydraulic or mechanical actuators are undoubtedly much more performant but the production and repairing of cutting forms is the bottle neck stage in the present circumstances.*

2. Cutting of fabric elastic band (or rubber ribbon).

[1] It is also possible to shape the part using both a cutting press or a water-jet cutter

- hot knife for cutting synthetic fabric or fabric elastic bands to simultaneously cut and secure the cut edge from unraveling. A cheap household soldering iron 80 … 400W ($3) with an initially thick but manually sharpened stinger was applied to reach the resulting performance of up to 1 cut per 2 seconds. The process requires appropriate fume extraction! (Figure 5).

- CAM hot knife that is available in specialized sewing workshops.

- conventional scissors can be used to significantly accelerate cutting process up to more than 30 cuts per minute while cutting 3 tapes simultaneously. A guillotine-type hand cutter (60 cuts per minute, 6 tapes at the same time) is also an option. Mechanical cutting of fabric elastic band, however, deteriorates the performance of fabric elastic band due to the unraveling.

3. Assembling the front flap, forehead strip and elastic band. In all types of design, this is done manually.

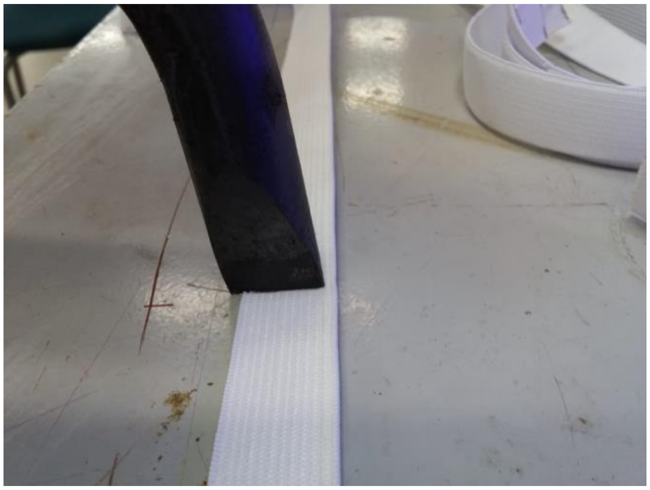

Figure 5. Cutting of elastic band by means of hot knife – soldering iron.

PRODUCTION EFFICIENCY AND LABOR OF DISTRIBUTED VOLONTEERS

Given the purpose of the work in the COVID-19 circumstances, it is likely that the workshop management is able to allocate 100% of the time for free. After simple training in the basics of labor safety rules and the practice of “one button " method for safe and effective operation, an operator can service either 2 units of laser cutters at a time (if they are installed side by side) or 1 laser cutter, but clean the corners of the face shield from the residuals of sheet material and protective transport film present on the surface of PET sheet meanwhile.

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Chronometry tests show that for the **Scheme A** 1 operator having access to the workshop (equipped with 1 laser cutter with a 1000x2000 mm desk and 1 soldering iron) is able make in 1 hour up to 70 sets of "front flap + forehead strip + fabric elastic band after a hot knife". Meanwhile up to 50% coefficient of cut parts may be pre-cleaned out of residuals even when operator has some rest.

Scheme B assumes that 1 operator in the workshop is using 2 medium-sized or small-sized cutters and 1 soldering iron. This scheme gains up to 150 sets per hour of "front flap + forehead strip + fabric elastic band after a hot knife" sets without cleaning. Then, a volunteer collects the sets in plastic bags for further assembling at home with a production efficiency dependent on the previous hand work experience and skills (we witnessed the efficiency of more than 30 assembled shields per hour). A volunteer courier can also deliver the sets to local delivery automats reducing the number of social contacts. Then the assembling work is carried out at home, taking into account quarantine measures. Undoubtedly, the assembling by end user can be performed at site which takes up to 4 minutes first time ever and less than 2 later on.

Optimal delivery and assembling production efficiency seems to be about 250 pcs (in 1 day with intense workload) or up to 750 pcs (for 1-week delivery - to reduce logistics costs and social contacts, when assembling is being performed by few jointly quarantined persons – an average family). It is worth to note that a strong motivation component is present: it is relatively easy to make a significant contribution in the form of real help. In this case, any starting skill set is suitable. The delivery of ready products to the hospitals is performed in the same manner, i.e. delivery automats and volunteer courier community.

FURTHER DEVELOPMENT AND OPTIMIZATION

The ability to increase the production efficiency in the scheme above are limited by performance of laser cutters, though up to 2 times growth due the higher cutting speed or cutting of two sheets at a time are possible. Production efficiency per 1 hour/1 operator can be enlarged up to 4 times if laser cutters of large area closely installed in the same workshop space are used.

Increasing the number of cuts with a hot knife is possible if a simple mechanical device pulling a number of parallel elastic bands to cut several bands with a long hot knife is utilized. Cutting a stack of bands is not recommended since the baking of bands to each other takes place. The use of a CAM hot knife would be optimal, but this equipment is rather available in specialized workshops.

The increase of cleaning operation performance can be realized when a special U-shaped tongue is coded to be cut on one side of sheet to facilitate the removal of the protective film.

The assembly takes from 4 to 6 times more time than cutting operations and it is recommended to be carried out by an end-user or a volunteer. Thus, a set of 500/1500 assembly kits sets is optimal for several days of work for one volunteer. 240L garbage bags (or any other) can be used repeatedly for the transportation.

The assembly kit includes:

- The front flaps and the forehead strips.
- Pre-cut elastic bands. It is necessary to prohibit cutting with a hot knife without the appropriate breath protection.
- Assembly instructions.
- Bags for product packaging.

VARIATIVE DESIGN

Taking into account different anatomical structure of heads (e.g. large male and children younger than 10 y.o.) universal size seems not to be applicable – see Supplementary Materials. Thus, adult and kid versions are supposed for full-day wearing. Up to 1 hour adult size is suitable for 4+ y.o.kids. The shape can be adapted to allow wearing the shield with a spun bond medical mask made, with a respirator and other breath protection means. It is also possible to radically reduce the area of the face shield - in this case, the product can be used as protective panoramic glasses.

The extended versions (both in up and down directions) are possible and the forehead part with a layer of polymer foam to increase the protection shown in the Figure 1a is the easiest development.

STERILIZATION AND SERVICE LIFE

Due to the use of reliable components, the service life of the shield is limited mainly by careless operation. In particular, it is important to carelessly store the " front surface on the table” - this creates scratches interfering comfortable view. The elastic band can be used for a long time without visible degradation. Careful operation should lead to a comfortable service life of about 1 working month.

Disinfection/sterilization methods have been successfully and repeatedly tested:

- Alcohol 70% + chlorine antiseptic (0.05% in water) 30%
- UV.

The design is specifically suitable for fast sterilization allowing to:

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1. Dispose contaminated elastic band thus "disassemble the face shield completely", sterilize 100% of the surface and assemble it back with new elastic band (3 spare ones are usually to be included). It takes 5 minutes (1 to disassemble, 2 for disinfection, 2 for re-assemblying)
2. Manage the elastic bands amount per end-user facility (usually over 500 within one building) and receive additional packages.
3. Significantly increase productivity by sending 80% of face shields as "assemble kits" to the end-users.

FIELD TESTING

Currently FabLab of Skoltech produces up to 2000 completes per day supplying medical hospitals, police departments and bank clerks in Moscow City and Region.

CONCLUSIONS

COVID-19 pandemic dramatically challenges society to find technical solutions for fast mass production of low cost personal safety means to protect medical personnel and ordinary citizens. In the situation when material sources are limited by the restrictions on trading and transportation and manpower is quarantined these technical solutions must rely on the designs suggesting simplest tools operated by minimal number of operators. CAM technology realized as the cutting of sheet materials by means of widely available in university workshops and fabrication laboratories is viewed as optimal for fast mass production of parts to be assembled by a community of volunteers or end users at site.

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