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Manufacturing Resilience during the Coronavirus Pandemic: On the investigation of Manufacturing Processes Agility

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Abstract

The unprecedented events that worldwide population experienced during year 2020 due to the COVID-19 pandemic, resulted in the formation of numerous challenges across the majority of aspects of every day life. Manufacturing industries and supply chain networks faced a unique decostruction during this period due to restrictions created by global or local lockdowns. Reduction of human resources availability and transportation restrictions linked with the extreme and rapid increase of demand for medical supplies led manufactring related activities to reach their limits. Moreover, the non flexible manufacturing methods that are employed for the production of this type of equipment as well as the delayed delivery of products that are used as raw material at the early production stages, resulted in market shortage of medical supplies while demand constantly growing. As a matter of fact, various production models and manufacturing processes had to be used at different phases, due to different levels of resilience. Automotive industry in particular tested corresponding processes' agility by transforming production and speeding up the production of medical equipment with alternative ways. However, the formal identification of the problem as well as the quantified requirements of each manufacturing method have to be evaluated in order to extract meaningful results that identify the reasons why traditional manufacturing facilities faced such difficulties in the production of medical equipment and to propose a roadmap where Additive Manufacturing methods can be used for the immediate, local and low volume production of the desired product, giving time to non flexible industries, such as Injection Molding, to initiate the mass production. To assess the presented methodology, a comparison between two different manufacturing methods for the production of a respiratory component has been used as case study. Finally, a hybrid manufacturing model is suggested.

Keywords: Manufacturing Process; Agility; COVID-19; Medical Equipment; Manufacturing Network

1 Introduction

To understand how the manufacturing paradigms have been utilized during the years and how they can be applied systematically for crises like the COVID-19 pandemic, first, the modern business model has to be determined. The modern business model points out that individual businesses are not capable to compete each other alone, leading to the development of industrial alliances *(Douglas, Cooper, 2000).* In the meantime, the complexity of modern devices asks for cooperation between industries from different sectors while the guideline of European Union for Corporate Social Responsibility (CSR) leads industries to follow a social profile, by respecting the laws and the competition with other industries. The main goal is to follow the pulse of the society in order to going side by side with the customer needs and finally raising their profit (*Corporate Social Responsibility & Responsible Business Conduct,2020), (Yildiz, 2014)*. By following this directive, as well as the need for humanitarian engineering and in particular response to emergencies (*Papacharalampopoulos et al, 2020),(Tayler,2016),* industries have been been been organized to consortia in order provide the required products while supporting each other. In this critical period the networks of business relationships and the willingness of individuals to support their National Health System to fight the COVID-19 virus (*Fauci et al,2020*), led to the creation of Hubs that work as supply chains in order to produce equipment which is under market shortage *(Carayannis, Zedtwitz,2005)*. Furthermore, it is highly desirable to address the concept of manufacturing resilience *(Gu et al, 2015)* through the manufacturing processes agility.

The absence of medical equipment can be explained considering that the developed countries, mainly the Western world, imports this equipment from countries which are located far away where the labor cost is low. Despite the fact that the transportation cost is high, the excessive profits seem to counteract these costs. The high delivery time and the increased domestic demand for medical supplies, followed by the local lockdown, resulted in increased demand in countries with many cases, leading to worldwide shortages *(Shokrani,2020)*. Decentralized production structures and AM Hubs tried to face this situation by adding flexibility to manufacturing processes in order to reflect local customer demand, by increasing the sustainability due to less distance that a product has to travel until the final destination, providing lower logistics, lower costs and shorter delivery time. From the beginning of this crisis it was evident that decentralized production structures have to be supported *(Shokrani,2020)*. In addition, the investments in education, learning & teaching factories, as well as the Industrial Research and Development played a significant role in the fight against this disease; without R&D and commercialization of AM as well as the domestic and small scale production, the situation would be worse. On the other hand, hubs took advantage of commercial platforms in order to provide details and knowledge to inexperienced people and hobbyists that possess AM devices. To this end, everyone could learn how to produce the required equipment following the product specifactions. Furthermore, reverse engineering and 3D scanners deployed to copy the different designs of the various equipment. In some cases, such as CPAP devices, the complex design asks for innovative and flexible solutions from the industrial world in order to develop an exact copy of the part *(Odena,Valls, 2020)*. In the meantime, chemical and pharmaceutical industry is really having a sprint in order to achieve some sort of attack to the virus with some sort of mechanism *(Panoutsopoulos, 2020)*.

The several manufacturing processes is a result of the technological improvements of the modern world, leading to different methods for making the same product (Florusse, 1992). Based on the material and the production volume target the suitable manufacturing processes may vary. For every manufacturing process a different infrastructure is needed (Chryssolouris,2006). AM on the other side, is a non-conventional manufacturing process which is able to cover small production volume with small production rates. However, it is able to adapt in different applications without excessive preparation time and labor cost *(Bikas, Stavropoulos, 2016)*. Numerous AM printing methods are available. They are categorized based on the printing mechanism and the printing material. The application, the user experience and the needed investment, are parameters that define which of the available machines is more suitable in every case *(Bikas et al, 2016), (Stavropoulos, Foteinopoulos 2018)*. Currently, several models and studies have been developed in order to simulate the AM processes and predict the product quality *(Stavropoulos, Foteinopoulos 2018),* the Build Time *(Komineas et al,2018)* and the consumed energy *(Peng, 2016*) while optimum sets of process parameters are available for different materials and printers *(Edwards, 2003), (Cantrell,2017)*. The above-mentioned work aims to make the AM processes predictable in terms of performance while the non-experienced users are able to create the desired product without being anxious for the selection of process parameters.

Apart from the utilization of AM in automotive, aircraft, aerospace and consumer product industry,etc., AM has been applied also in medical industry in different fields such as dental use, prosthetic arms development *(Mohd, 2018),* integrated human tissues in prosthetic members etc *(Partee, 2006)*. During COVID 19, AM has been involved in the production of Personal Protective Equipment (PPE), which is a number of parts that consist a set of medical protective equipment that can be used either multiple times or for one use and protect the population from getting in touch with diseased people and breath polluted air as well as in the production of breathing aids devices *(Haleem, Javaid, 2020).*

Due to the lack of the literature and the novelty of the effect of COVID-19 in every aspect of everyday life as well as in manufacturing processes, this paper aims to investigate corporate responses and case studies that have been adopted during this pandemic crisis as well as **to introduce an adaptive framework** that can be used in order to face similar crisis, quantifying the response-related capabilities of manufacturing processes. The structure of the paper follows the investigation of the facts that took place during the pandemic crisis, in chronological order. In Section 2, the methodology of this work is mentioned while in Section 3, the phenomenology of the factors affecting the demand is presented. In Section 4, the Personal Protective Equipment for the hospital staff is documented along with the devices in market shortage during COVID-19 pandemic outbreak as well as the contribution of industrial world in the production of the aforementioned equipment is mentioned. The capabilities of the traditional manufacturing methods for the production of the abovementioned clothing and devices are described in a more systematic and quantified way in Section 5. In the same section, the presentation of the formation of Glocal hubs and their activities can be found. A **roadmap is then sugested** therein based on the KPIs of production that are relevant to manufacturing resilience and manufacturing processes agility. The relationship between the production rate and the required time for the production of a medical equipment with a flexible, a non-flexible manufacturing and a hybrid method in order to cover the local and global demand is mentioned in Section 6.

2 Methodology

This work aims to access the traditional manufacturing methods for the production of plastic/metal medical supplies in terms of flexibility/requirements and to understand what were the reasons that led to shortage of medical supplies and Personal Protective Equipment (PPE). To achieve that, different sources of information have been considered in order to gather the necessary material and understand the chronological sequence of events related to pandemic outbreak as well as to find out what kind of medical supplies and protective equipment are needed to face this crisis. Moreover, there were lot of articles, indicating the contribution of the industrial world to that effort. From all the industrial world, automotive industries stood out because they were organized quickly and they speeded up the production of medical supplies such as (breath aid devices, surgery masks etc.) that were given to local hospitals in order to face urgent cases. At the same time, individuals and hobbyist were also organized to create medical supplies with low production volume, but with less transportation cost and delivery time. Later on, many more industries begun the production of medical equipment, taking as granted the proper design of the final product. Having gathered and studied the aforementioned information, it is crucial to investigate the working principles of traditional manufacturing methods that were capable to undertake the production of such equipment and divide them according to their characteristics, on flexible and non-flexible manufacturing processes. This division determines how easily they can adopt to the production of different products and production volumes. To do that, data from literature was used and analyzed.

The analysis of the obtained information and the better understanding of manufacturing hubs led us to define the Glocal Hub Manufacturing model that is capable to merge the high volume production of industrial world with the low volume production of individuals and restructured distribution networks in order to match the demand in medical supplies, locally and worldwide. The principles of this model and how exactly it works, can be seen on the related section (Section 5.1). To this end, it is evident that the developed hybrid manufacturing model needs to be agile and flexible to provide with the desired products under variable production volume and time. The resilience of the hybrid manufacturing model can be defined as the ability to withstand and counteract disruptions and after a number of steps to recover to the normal conditions. This system can be flexible and one of the main features can be the workload reallocation that depends on the availability of raw material and machines (*Xi et al, 2015*). The next important feature of the proposed hybrid manufacturing model is the agility of the involved processes. Agility is the capability to respond effectively to the requirements of the existing market demand. As an example, to reduce the process cycle time and increase the productivity rate as well as to produce a different design of a product without excessive preparation time (*Bessant et al, 2000*). All these factors could be integrated into a methodology of assemblying the proper criteria and interpreting them them into

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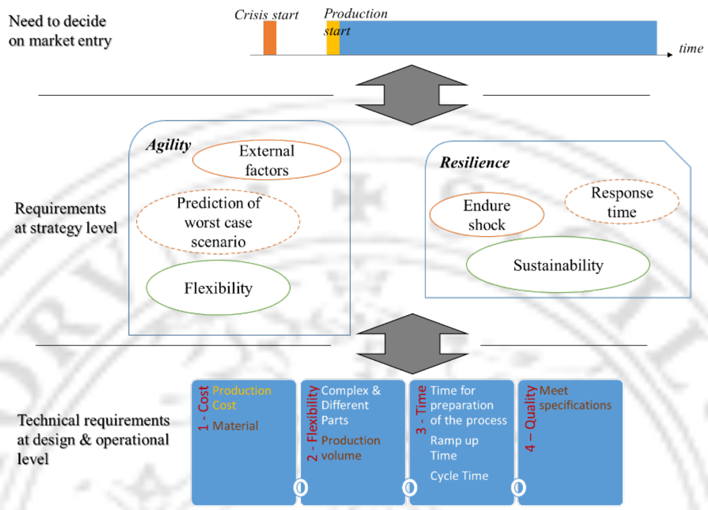
technical specifications (*Figure 1).* The matching of the various KPIs can be considered a continuation of previous works on KPIs interlink for decision making (Papacharalampopoulos et al, 2020).

Figure 1: Agility and Resilience in Manufacturing Processes, integrating definitions



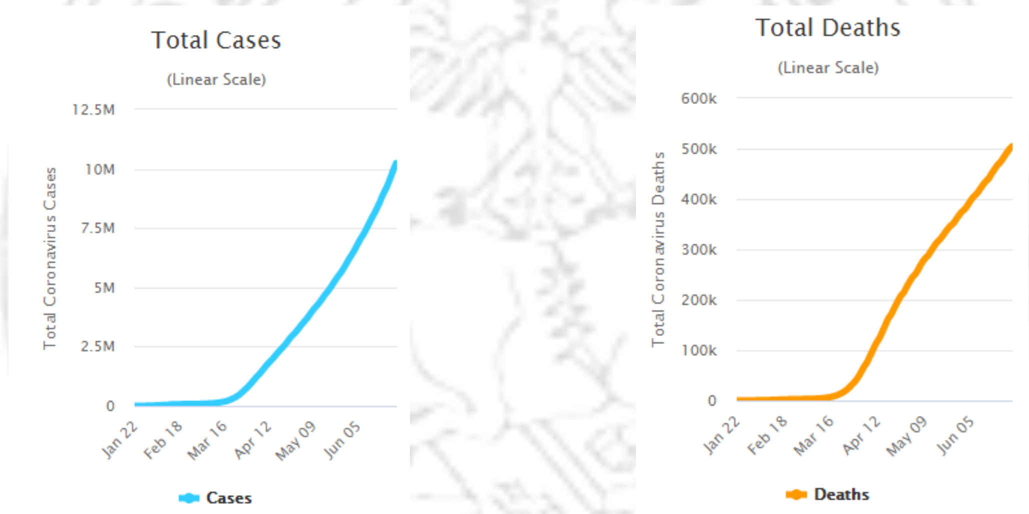
Source: [Fayezi et al, 2017],[Ahern, 2011]

As it can be observed from this methodology, the present work can be seen as an adaptive framework which can be employed in similar crisis were shortage of an equipment exists.The presented methodology refers to this unique occasion of Covid-19 pandemic crisis. Each occasion is governed from different characteristics that have to be studied and evaluated in order to extract a reaction plan, through a roadmap. The technical specifications have been set so far, through adoption of criteria, either on/off, denoted in brown font color in Figure 1 bottom schematic, or as desired, annotated in yelow colour and the ones that are of priority (white ones). To achive extracting a roadmap, however, the comparison of different manufacturing methods must be conducted (end of section 5.1), providing with details regarding the characteristics of each method as well as their capabilities. For the assessment of this framework, a respiratory component is used. The comparison between two separate manufacturing methods (Injection Molding and Additive Manufacturing) in terms of production volume and cycle time, proves that a hybrid solution is required along-side with the restructured distribution network with the aid of Glocal Hubs in order to face this difficult situation. In brief, Additive Manufacturing can provide parts at small production rate and volume until the mass production manufacturing methods reach the desired production rates.

3 Phenomenology of the factors affecting the demand-production equilibrium

The first confirmed cases of COVID-19 infections (due to virus SARS-CoV-2) appeared at the end of 2019. After a few months, this situation evolved into a pandemic with millions of diseased people, because of the existing socio-economic globalization where citizens from different countries communicate, work side by side, products are exported/imported and people are travelling across the world to meet new civilization and cultures. The worldwide spread of the virus created an medical supply demand for which the medical suppliers were not prepared to cover, leaving hospital's needs for equipment unmet. **Errore. L'origine riferimento non è stata trovata.**a represents the total confirmed cases over time while the **Errore. L'origine riferimento non è stata trovata.**b shows the number of deaths caused at the same time.

Figure 2:(a) Number of cases, (b) Number of deaths

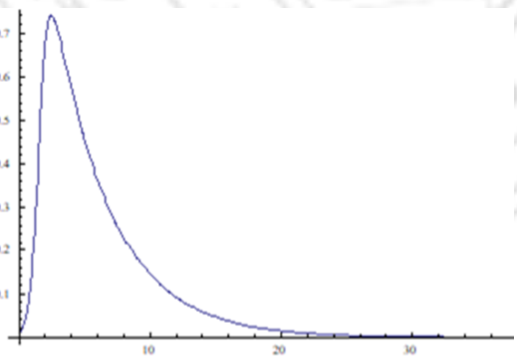


(a) (b)

Source: Covid-19 Coronavirus Pandemic,2020

The moment that confirmed cases raised rapidly is the exact same moment that the number of deaths increased accordingly. To face that situation, the medical suppliers had to increase the production in order to match the hospital demands. At hospitals, the infected people with severe symptoms, such as pneumonia (*Zu et al, 2020*), were under medical care with special equipment such as breathing aid devices, air control valves, etc. and the hospital staff was obliged to use continuously the Personal Protective Equipment and replace it in short time intervals, in order to protect themselves and prevent the virus spread *(Coronavirus disease (Covid-19) pandemic, 2020)*. Moreover, during this period the pre-arrenged medical meetings or surgeries were rescheduled in order to save medical supplies that can be used to fight the pandemic crisis, leading to death people with sever diseaces such as cancer (*Spinelli, Pelino, 2020*). To this end, the necessity for medical supplies mass production was intense and unpredictable while in most cases the suppliers could not quantify demands. In order to produce at a higher productivity rate, production line adjustments/optimization required. However, the medical suppliers had to cover the worldwide high demand, making of utmost importance the contribution of individuals, research center and industries, in medical equipment production. The following plot represents the infected percentage of population over time. It has been produced based on the equation of the SIR model *(Nesteruk, 2020)* and illustrates a bad scenario where even up to 70% of the population is infected rapidly. The vertical axis represents the percentage of population that has been infected for a certain time period while on the horizontal axis the time period, measured on days, can be seen. The evolution of this situation has indicated that measures such as social distancing had to be applied in order to avoid the virus spread. The abrupt increase of diseased suggests the need for handling a lot of cases at the same time. The provision of personal protective and hospital equipment are prerequisites for the curing of diseased people and the reduction of new infected cases. This procedure lasts over a long time period, until the curve is flattened which means that the virus spread has been minimized *(Haleem, Javaid, 2020)*(***Errore. L'origine riferimento non è stata trovata.***).

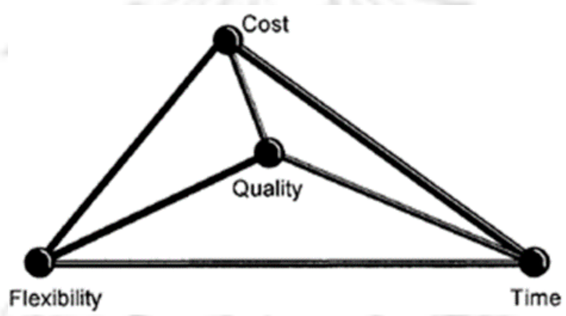
Figure 3: Infected percentage over time



Source: Haleem, Javaid, 2020

During the lockdown period, companies and industries were closed, the individuals were working from home while research centers were opened, following at the same time the protective measures. People with the necessary knowledge combined their forces to serve the national health system of their country, producing the required protective equipment and breathing aid devices (*Designs for Live-saving Breathing Aid to be Made Freely Available, 2020)*. Thus, with the aid of reverse engineering, the accurate design copies of several parts were available, while the final products were created by taking advantage of Additive Manufacturing techniques for plastic and metal printing. The domestic production and the small-scale production from research centers could not meet the raising demand so there was need for transformations in the production line of big factories e.g. automotive industry etc. According to Chryssolouris *(Chryssolouris, 2006),* there are four classes of manufacturing parameters to be considered when making manufacturing decisions: cost, time quality and flexibility. These decisions, depend on the particular problem, specific objectives, goals and criteria (***Errore. L'origine riferimento non è stata trovata.***).

Figure 4: The Manufacturing Tetrahedron



Source: Chryssolouris, 2006

Meanwhile, the situation had been getting worse. Therefore, the transformation of factories for medical supplies production had to be based on the flexibility of the production line, in order to create as soon as possible the first products to share to the hospitals. The products quality had to be fair enough to serve their cause while the productivity rate to be high to match the demand. The aim of the present work is to identify which of the existing manufacturing methods are enough flexible to deal with the sudden/unpredictable increase in demand, in medical supplies during COVID-19 outbreak. On the one hand AM has proven its potential, in small scale/domestic production, covering the local needs, while on the other hand, AM low productivity rates indicates that this manufacturing method is not capable to match the rising hospital demand, worldwide by producing in mass production medical supplies *(Kose, 2020), (Baumers, 2015).*

4 Paradigms of medical parts in high demand and the response of industry

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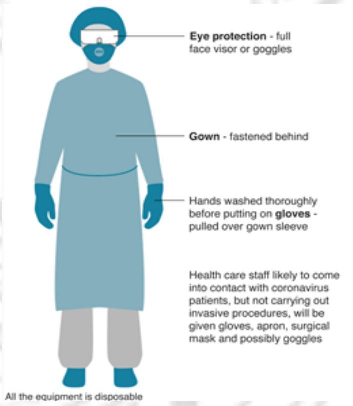
Based on available evidence and medical surveys, the SARS-CoV-2, the virus that causes COVID-19, can be transmitted among the population either on close contact via hugs, handshakes and kisses or travel longer distances during talking, sneezing as well as coughing *(Nesteruk, Igor, 2020)*. The ease of virus spread has led to more than 2.4 million confirmed cases *(Covid-19 Coronavirus Pandemic,2020*) since today upsetting the scientific community, making at the same time the use of Personal Protective Equipment (PPE) of utmost importance for people that are obliged to work nearby diseased people such as nurses, doctors, hospital cleaners as well as ambulance staff (*Source:*). Due to the nature of the virus contagiousness, the equipment has to cover the whole body, mainly the free of clothes, skin. The table below (

Table *1*) presents the safety clothing that it is considered as Personal Protective Equipment from World Health Organization (WHO) (*Coronavirus disease (COVID-19) pandemic, 2020) , (Yao, 2020).*

Figure 5: (a), (b) Safety clothes and personal protective equipment (PPE)

(a)



(b)

Source: Personal Protective Equipment (PPE),2020

Table 1: Suggested equipment for human protection

Protection	Suggested equipment
1. Respiratory protection	Face mask or surgical mask: N95, FFP2, FFP3 or equivalent
2. Body protection	Gown/ apron: Long-sleeved water resistant
3. Hand Protection	Safety gloves
4. Eye protection	Goggles or face shields

Source: Authors elaboration

Apart from the wearing equipment the COVID-19 pandemic outbreak has brought to surface the importance of equipment that is used in severe respiratory diseases. Meanwhile, the treatment in hospitals is based on the proper operation of assisting breathing devices. On the one hand the common breathing devices, without mechanical support, work on affected people without severe symptoms while on the other hand the Continuous Positive Airway Pressure (CPAP) is form of non-invasive mechanical ventilation, working as breathing aid, which applies mild air pressure on a continuous basis and keeps the airways continuously open in patients who are able to breathe on their own, but they need help keeping their airway unobstructed *(Ti, 2020)*. In addition, air control valves are responsible to control the oxygen that fills in the breath mask from an external respirator *(Ball, 2011)*. Without these valves the patient mask is not capable to work. In general, the aspirators/ventilators were in demand due to high numbers of intubation occurrences. These machines are generally expensive (*Li, Xiao, 2020) (Elling, Politis, 1983)*, consist of many different materials and also require assembly further to processing, while the production rate is bounded, according to Stefan Dräger who is the head of a ventilator manufacturer (*Top German ventilator company warns on global supply crunch, 2020)*. However, they can be reused once a patient exits intensive care. Regarding the consumables, however, they can be used only once, and they may need change every five days on average. Also, customized solutions often had to be taken into consideration, as often come across in the media from a number of sources like the Brussels (AFP) hospital. The main difference in addressing manufacturing of such equipment is that masks can be manufactured in a distributed, home-made way, even though the demand is high (even 70% of the population may need them daily according to **Errore. L'origine riferimento non è stata trovata.** from NHS, while valves (*Figure 6b*) require machine tools and the demand occurs at bursts and is a bit lower, involving only the intubated patients *(Yao, 2020)*. The treatment also implied demand for continuous processes, like hospital-related gases, medicine, and disinfectants *(Ti, 2020)*. Furthermore, it is worth noting that applying circular ecomomy policies in this particular case may be hard or even unacceptable due to the protocols existing, and due to the fact that the virus has not been previously met by medical experts or authorities *(Chartier, 2014).*

Figure 6: Devices

(a) (b)

Sources: (a) CPAP Device (Designs for Live-saving Breathing Aid to be Made Freely Available, 2020), (b) Air control valve (3D CAD File: Respirator-free reanimation Venturi's valve, 2020)

4.1 Link to capabilities of existing lines

Although many industries have contributed to this fight, automotive industries are studied due to the fact that they take advantage of cutting-edge technologies which are used from skillful operators, as well as, flexible and non-flexible manufacturing processes and it is worth to see how they reacted in order to cover the demand of medical equipment that faced shortages. Apart from actual products, many industries circulated the 3D desing of a medical equipment(respiratory components) to individuals, in order to create the desired part with the appopriate quaility and under the requested specifications. Car manufacturers and other industries accompanied by the traditional suppliers of medical equipment have been organized in order to address the spike in demand by speeding and scaling up the existing production. The World Health Organization (WHO) has published a list of COVID-19 critical items facing global shortage such as gloves and masks (*Table 2*).

Table 2: Critical items that face global shortage

Category	Critical Items identified by WHO	Example of facilities that might be repurposed
Protective Person Equipment (PPE)	• Gloves, examination • Gloves, surgical • Goggles protective • Gown, protective • Face shield • Mask, particulate respirator • Mask, surgical	• Textile factories • Garment plants • Yarn spinning mills • Electronic assembly plants • Injection molding facilities • Prototyping shops (3D printing)

Diagnostic Equipment	• Lab screening test kit • Lab confirmation test kit • RT-PCR kit • Extraction kit • Cartridges for RT-PCR automatic systems • Swab and viral transport medium	• Pharmaceutical preparations • Biopharmaceutical preparations • Pilot biotech plants • Clinical research laboratories
Clinical care equipment	• Pulse oximeter • Concentrator of gas • Nasal Oxygen cannula, with prongs • Ventilator patient, for adult, pediatric • CPAP with tubing and patient interfaces for adult and pediatric • Suction pump, mechanical • High-flow nasal cannula (HFNC)	• Automotive production lines • Aerospace manufacturing plants • Specialized engineering service and testing facilities • Manufacturing technology and innovation centers • Vacuum cleaner assembly plants • Machine shops

Source: Authors elaboration

In modern manufacturing, production processes can be highly automated and specialized aiming to maximize the productivity rate. The approach of lean manufacturing tends to eliminate waste across the production line and improves productivity. Although a highly efficient and profitable production can be developed, it is extremely difficult to transform the production line to produce a new part. Several industries face difficulties to reach the desired level of quality and performance in short time after the initiation of a new production line. However, the attempts continued in order to tackle the further expansion of the disease by covering the needs in medical supplies, making possible to cure several cases by protecting the hospital staff, Most of the industries participating in the global effort mainly produce masks, respirators and head mounts for the face shields. The response of the automotive industry is analyzed indicatively below. During this period GROUP VAG was capable of producing face shields (350 units per day), automated ventilators (13 prototypes) , reusable respirators (60 per day), and surgical masks (1000 per day) while PSA and FCA groups were producing respirators (200 per day), visors (30 per day) and masks accordingly. The experienced manufacturers and industrial consortiums not only transformed their production line to create the required equipment but also, by working side by side with the traditional medical suppliers achieved to share their knowledge in how to improve their production rates. In some cases, industries lent equipment, mainly 3D Printers, to research centers in order to manufacture simple equipment for the protection of local hospital staff (*Table 3*).

Table 3: Car manufacturers contributions (Mapping the auto manufacturers building PPE and medical equipment to battle COVID-19, 2020)

Manufacturer	Product	Partner	Details
BMW	Ventilator parts	None	Utilization of the 3D printers
Ferrari	Ventilator parts	Siare Engineering	Supercar maker is preparing to manufacture parts at its factory
Fiat Chrysler	Ventilator parts/ Masks	Siare Engineering	-Siare notes that carmakers have more component purchasing power than it does. -Aiming to distribute to emergency workers and first responders initially.
Ford	Ventilators	GE Healthcare	Rawsonville previously made oil pumps, battery packs, induction systems, ignition coils and fuel pumps
General motors	Ventilators	Ventec life systems	Kokomo previously made electronic and semiconductors components
Jaguar Land Rover	Masks	N/A	Its own design utilizing its 3D printing capabilities
Linamar	Ventilator parts	O-Two Medical Technologies	Partnership between Linamar, Magna and Martinrea to provide parts for ventilator designs
Mahindra	Ventilators	Unnamed ventilator producer	Manufacturing face shields and working on developing a low-cost ventilator design that will cost less than 7.500$ per unit
Magna	Ventilator parts	O-Two Medical Technologies	Partnership between Linamar, Magna and Martinrea to provide parts for ventilator designs
Marelli Corporation	Ventilator parts	Siare Engineering	Discussions are being held to confirm whether Italian manufacturers will build parts themselves or increase Siare's capacity
Martinrea	Ventilator parts	O-Two Medical Technologies	Partnership between Linamar, Magna and Martinrea to provide parts for ventilator designs
McLaren	Ventilators	Consortium	Joined a UK consortium to develop an emergency ventilator for rapid deployment
Mercedes F1	CPAP devices	None	Developed and building a CPAP machine which could reduce the need for medical ventilators by keeping the patients out of intensive care
Nissan	Ventilators	Consortium	Joined a UK consortium to develop an emergency ventilator for rapid deployment
SEAT	Ventilators	Protofy XYZ and others	The design uses 3D printed gears and a repurposed windscreen wiper motor from the SEAT Leon and is made on the Leon subframe assembly
Tesla	Ventilators	Medtronic	Aiming to develop its own design using many parts repurposed from Tesla cars
Toyota	Masks Filters	None	Preparing to 3D print face masks for emergency personnel and preparing to produce filters for respirator and ventilator use.
Volkswagen	Ventilator parts	None	The company is looking to utilize its 125 industrial 3D printers to build ventilator parts

Source: Authors elaboration

The contribution of Additive Manufacturing in that effort seems to be of utmost importance due to the flexibility of the process which gives the possibility to everyone possessing a 3D printing machine to create/develop a part, without manufacturing experience. The solution of Injection Molding follows as the process which is ideal to produce a significant volume of products in specific time. That process also involves the development of molds and the machine set up, assuming the existence of the machine in a facility.

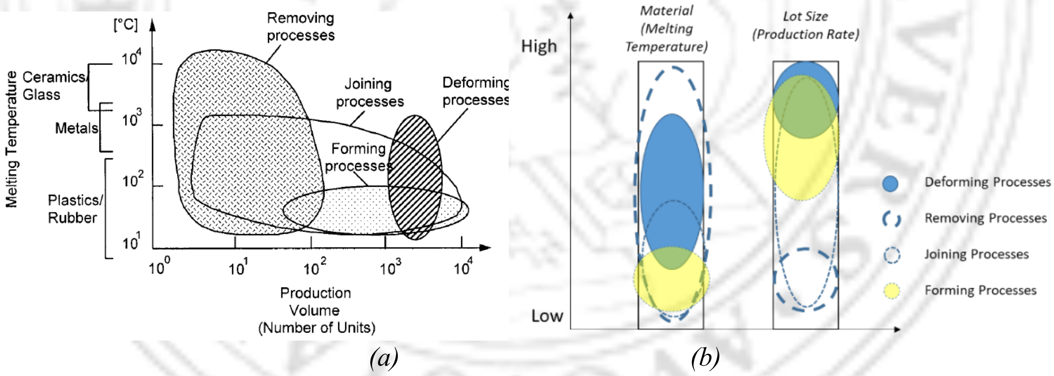
5 Capability & Agility of Manufacturing Processes and Manufacturing Resilience

5.1 Quantifying the Processes capabilities

The centralized mass production for medical supplies made from plastic takes advantage of the forming processes. In the industrial scale it is crucial to produce with high productivity rate, low cost, and fair product quality. Moreover, the production has to be flexible enough to produce a variety of products without wasting time and money to change the equipment every time that a new design comes to the production *(Chryssolouris, 2006)*. In

Figure 7 the recommended manufacturing processes for several materials can be seen, considering also the production volume and the melting temperature of the machined material. The estimated production volume for medical supplies like face shields, face masks etc. is identified between 10^2 and 10^6. Therefore, the forming processes seems to be the preferable for that kind of production. The diagram has also been reformed to an axes form, showing the two criteria independtly.

Figure 7: Manufacturing processes vs material



Sources: (a) Original form of the diagram (Chryssolouris, 2006), (b) reformulated form of the diagram

According to Chryssolouris (Chryssolouris, 2006), forming processes are divided into casting and melting processes. The casting process involves the effect of gravity during the filling of the mold while the melting process takes advantage of applied pressure to process viscous polymers, at high temperatures, forcing the material to flow under the effect of gravity. For plastic material, the molding process correlates with melting processes, which takes place with the aid of a mold, similarly to casting process in metals. A wide range of molding processes can be found, namely; compression molding, transfer molding, injection molding, extrusion, reaction injection molding, rotational molding, calendering, and melt spinning. The characteristics of the forming processes are included on the table below (Table 4). In this study it is important to have bear in mind that non-dedicated for medical supplies factories have to be transformed in production lines with high production rate, fair quality to protect the medical staff and assist the diseased people as well as low labour cost. Assuming that the transformation is possibly to happen on industries with facilities to create the mould and then proceed to the injection molding for the production, the cost can be maintained on low levels for tooling, while the transformation period can be significant small.

Table 4: Forming process characteristics

	Cost	Production Rate	Quality	Flexibility
Forming Processes	High Tooling/Low Labor cost	High	Medium to Low	Low

Sources: Chryssolouris, 2006

The above-mentioned characteristics there are available for every process explaining the reason why industries decide to run the production with the aid of certain processes based on four main indicators:

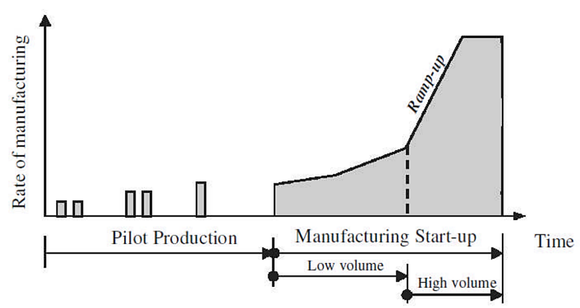
a. Material selection
b. Manufacturing of complex designs.
c. Time for the preparation of the process (molds, machine process parameters, etc.)
d. Production Rate
e. Ramp up rate

The meaning of the first three terms can be easily extracted. The material term refers to the choice that engineers have made to be used for a certain product based on its properties. The material choice is the first step for the development of a product and manufacturing process selection. Figure 8 shows preferable processes for the manufacturing of products based on their raw material. If the circumstances lead to change the raw material, then, all the production process has to change as well as the design of the product. So, there is a strong relationship between the product design and the raw material choice, explaining why the design is the second step of the process selection. The product design guides the manufacturing process. Complex parts spend too much time in manufacturing processes (one dedicated machine or more machines based on the manufacturing phases) while simple designs need significantly less time. Moreover, the part design defines the required equipment to run the process. As an example, for injection molding process male or female molds are required.

The complexity of molds design (*Italian engineers support the fight against the COVID-19 virus by 3D printing valves to medical equipment, 2020*) and manufacturing is considered as extra time added to the final production time. Up to this point it can be extracted that on the one hand, for small production volumes and for immediate initiation of production, processes that require complementary equipment to run should be avoided, while, on the other hand, the extra time spent at the early stages of production (mold manufacturing/design) is covered due to the increased production rates that a process, such as injection molding, can offer.

Production rate refers to the number of units produced over time. The production rate can be expressed, when the production run smoothly, and the machines are optimized. At an earlier stage, the production has been tested in several scenarios, in order to examine if there are issues that can lead to faulty products. So, three stages can be pointed; a) pilot production when the first parts come out of the production and both the machines and the parts are under inspection to ensure, that the products follow the product requirements and the machines are in good condition; b) the low volume phase where the production line work at 50% of its potentials in order to control the production in terms of energy consumption, cost as well as the wear of machines; c) the high volume phase where the product quality, production volume, energy consumption etc. are optimized and they remain constant over time *(Ball, 2011)*. The last term ramp up expresses the rate with a production can address all the knowledge obtained during the low volume production in order to move to high volume production or from pilot production to low volume production. If the ramp up is low, then the production needs much time to alter from the one level to the other. The ramp up time as well as the different production phases can be seen below.

Figure 8: Production phases



Sources: Ball, 2011

Figure 9 aims to present how the five main process selection indicators affect each process. The scale 1(low)-5(high) defines the variety of different materials that can be processed on each process, the capability and agiility of processing complex designs, the required time for the preparation of each process and finally which one of the available processes can offer higher and lower production and ramp up rate. To this end, it can be said that this scale is a comparative means for the examined parameters. e.g. the ramp up rate for additive manufacturing processes can be equal to joining process and higher of removing process. This happens due to the process variables that are involved on the process; for removing processes, factors such as cutting fluid temperature and flow, cutting tool failures, workpiece placement on the table, process parameters selection etc. seems to reduce the ramp up rate, while in AM processes, less factors are involved such as process parameters selection and filament replacement after certain time intervals, leading to higher ramp up rate. A utility function derived from these five criteria could be defined, however, the current framework ought to take the five constituents separately into consideration, in terms of a five-dimension vector (or more formally like an array). This five-fold metric could be called as extended manufacturing process agility metric.

Figure 9: Process selection procedure (each component has a unique scale) utilizing extended process agility

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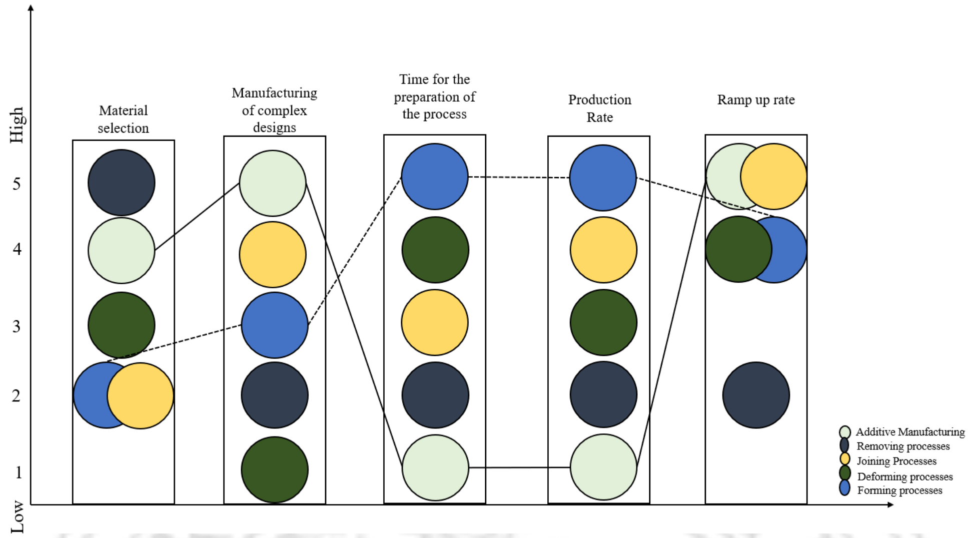


Source: Authors elaboration

5.2 Considering Glocal Hubs Manufacturing as a manufacturing model for enhanced resilience

The Glocal Hub Manufacturing Model is defined as numerous locally placed manufacturing subsystems that act together in a unified network to cover a demand that appears at a global level *(Trappey, 2007)*. The Glocal Hub Manufacturing system shares similarities with the hub-and-spoke system the airlines use to better cover the travelling demands from minor origins and destinations and at the same time remain cost efficient *(Cook, 2014)*. With an opposite mentality, the initial approach to cover a large part demand was to subcontract the overall need to a single supplier and after the production of the total batches is completed, the orders are divided and shipped to the locations in need accordingly. When time response is critical and demand spikes can occur, this singular supplier system indicates high risks of bottlenecking and failure. The three main causes were identified to be:

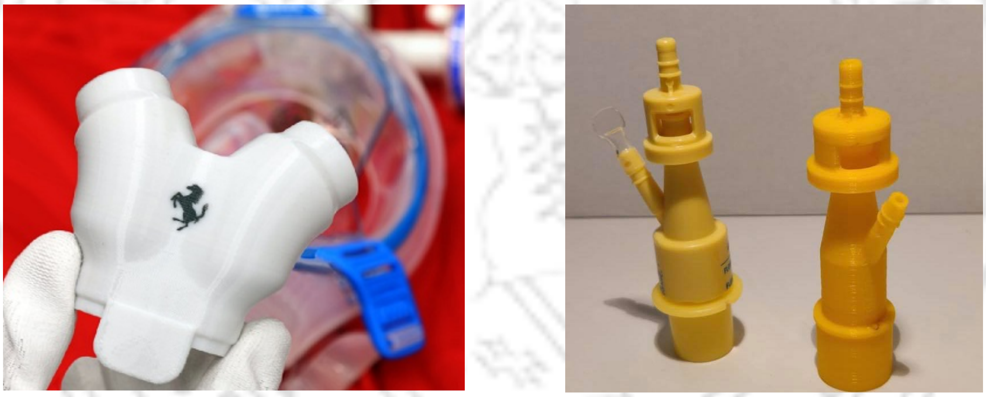
i). The singular supplier's production stops and requires additional troubleshooting actions and time to restart.

ii). The utilization and setup of additional manufacturing equipment for parallel production is cost intensive.

iii). The global shipping network is overloaded.

Implementing the Glocal Hub Manufacturing model for mass production compensates for the above risks of the singular supplier model. The large number of local manufactures, near the hub in the high supply need, secure that in the scenario of failure of a production line of one or more suppliers, the remaining functioning ones can intensify their production rates to supplement the failure or at least partially cover the supply demand. The ability to utilize additional equipment in a short time is process dependent. As an example, in the case of the respirators which faced excessive demand during COVID-19 pandemic, Additive Manufacturing machines were more efficient and flexible to set up the process and inititate the small scale production than Injection Molding machines. Finally, the organized Glocal Hubs cotributed to shorter traveling distance between the supply and demand which performed better in the case of a shipping network malfunction. The current circumstances regarding the COVID-19 outbreak created an absurd spike on the demand of medical devices *(Haleem, 2020)*. The identified medical components can be divided into two main categories; a) the ones that can be manufactured exclusively by a specific manufacturing process and b) those that with simple desing modifications can be manufactured via alternative ones (*Figure 10*, *Figure 11*).

Figure 10: Examples of additive manufactured



(a) (b)

Sources: (a) Additive Manufactured valve for emergency masks to assist patients suffering from respiratory failure (Ferrari continues its efforts to fight the Covid-19 pandemic, 2020) ,[b] similar valve for oxygen respirator were an urge, the right one (Italian engineers support the fight against the COVID-19 virus by 3D printing valves to medical equipment, 2020)

Figure 11: Face mask mold, injection molding for mass production

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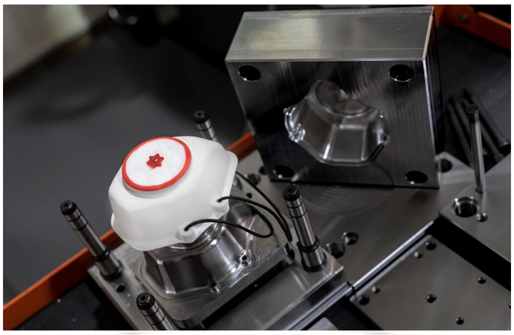


Source: Edition 2020, 2020

When it comes to mass production of medical equipment, the production is centralized, and the supplying distribution is realized via the shipping network. That is, the uneven equipment demands across the globe, combined by the bottleneck of the supply network between Asia and Europe resulted in crucial deficiencies of medical equipment. A profound solution was given to this issue by the Additive Manufacturing community, from individuals with both professional and desktop equipment. The medical components that were on shortage and that had part features that where AM manufacturable *(Bikas, Lianos, 2019)* were rapidly reverse engineered and manufactured in large numbers from users that acted as suppliers with access to AM equipment. The demand was thus covered via the localized manufacturing hub model. The small batch of approximately 12 pieces per print was counteracted by the number of the available equipment spread across European countries. Only Greece has an active 3D Printing community for plastic manufacturing that is estimated to be of more than 2000 individuals with at least one AM machine each.

To understand the better suitability of AM in the case of the COVID-19 pandemic the medical equipment demand and supply chain must be investigated.

i). The first point was that the overall demand increased in a short period of time.

ii). The second aspect was that the overall large number of medical equipment produced were to be distributed in smaller numbers among the hospital units that were facing shortage. This step in the supply chain was bottlenecked from the shipping networks that were also facing profound numbers in regional and international level.

The AM supply chain was in the contrary locally identified and evenly spread due to the low cost of the AM plastic equipment. This made the shipping more efficient as the hospitals were supplied by close-by AM suppliers. This alternative way was also not dependent on a singular standalone large supplier but on a coherent network of the AM community of small but numerous professional and amateur individuals. This resulted to the satisfaction of the demand spike more efficiently with AM compared to the Injection Molding supply. The idea behind the decision making for the most suitable process is to provide; a) rapid response from the initial demand spike to the first manufactured part and b) high production rates to cover the global demand in time. The parameter of time is the most critical parameter in that decision making framework.

These two system characteristics are contradicting for a singular manufacturing process. As the mass production capacity and pace increase, the agility of the system decreases, whereas a highly agile system is not capable of mass production. To abide to both specifications a hybrid system it seems to be more functional. The first subsystem can manufacture rapidly and produce initial batches to feed the demand (AM). This buys time for the second system to reach high production levels and cover the overall demand (Injection Molding)

6 Workflow adaptation for the production of respiratory components

To investigate further the mechanism behind this unprecedented supply chain, the respiratory component was chosen as a case study (*Figure 10*). The Additive Manufacturing(AM) and Injection Molding(IM) productions are to be compared for the manufacturing performance. All the different process steps and their relative durations were identified for a new supplier to initiate production (*Table 5)*.

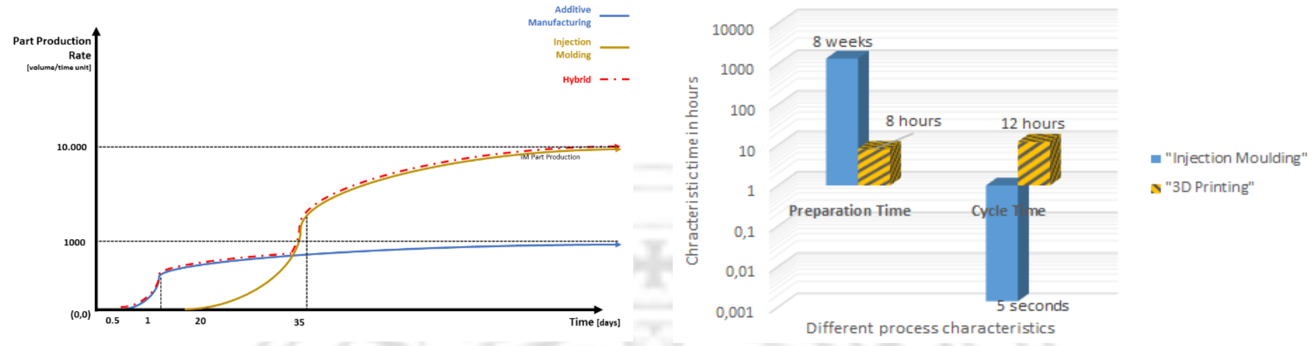
Table 5 AM and IM process steps comparison

Steps	Injection Molding	Additive Manufacturing
1	Part design for injection molding manufacturability	Part design for AM manufacturability
2	Mold design and manufacturing	Optimizing the process parameters
3	Optimizing the process parameters	Part manufacturing
4	Part manufacturing	

Source: Authors elaboration

In Figure 12, it can be seen that the AM response time for the initial part manufacturing is much shorter than the one for injection molding. This is due to the fact that the process steps from part design to the actual part manufacturing are fewer and shorter. The aforementioned quantities for the required time and production rate are an indicative average. The actual numbers are case dependent and can vary. That is, once the upstream steps are realized, the capacity and production of injection molding is far superior compared to AM.

Figure 12: (a) Compared process steps, (b) Comparing Injection Molding and 3D Printing: Preparation Time in IM concerns design of the mold, while in 3DP it concerns design of the part. based on authors estimation and literature



(a) (b)

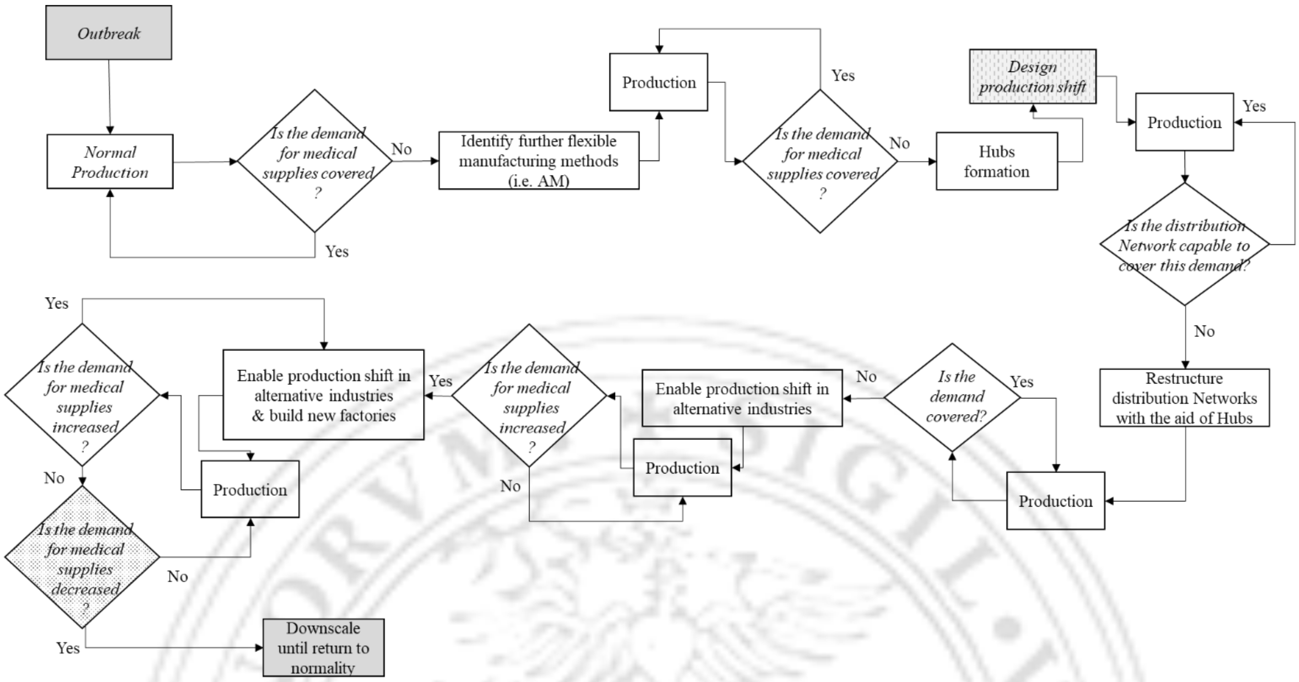
Source: Guidance for wearing and removing personal protective equipment in healthcare settings for the care of patients with suspected or confirmed COVID-19, 2020

From Figure 12 the utility function that measures the success of the decision making for the appropriate manufacturing method can be obtained. It is noted that the utility function, being a means to measure the success of a decision that is affected from different factors (*Pavan, Todeschini,2009),* due to the complexity of this application, remains to be an array of the aforementioned different aspects. Finally, the roadmap for the Covid-19 pandemic crisis, considering all the intermediate actions and steps that were necessary in order to confront this situation, can be seen below in Figure 13. In order for this framework to be taken into consideration, one has to take into account that there are two arbitrary assumptions under which it has been formed;

i). The question on the decrease of the demand (annotated in grey colour) should be not done after every step, as it has been considered unlikely to exit an emergency situation in short time

ii). The production shift should be designed early enough (the second grey box)

Figure 13: Roadmap for COVID-19 case



Source: Authors elaboration

7 Conclusion

The ongoing unpredictable socia-financial situation due to COVID-19 pandemic required special treatment in all different fields of everyday life. The industrial world reacted with its own means, taking advantage of the whole inventory of manufacturing processes, in order to cover the demand of medical supplies in a limited time space. The R&D and the commercialization of AM printers, followed by the development of local Hubs, created a network of individuals and traditional manufacturers that were capable to produce low production volume until the non flexible production lines managed to raise the mass production upto the desired levels. The industrial world, organized in consortiums, has provided technologies and infrastructures to face that situtations. The Corporate Social Responsibility (CSR) ideal created the pillars and guide the industrial world to this effort. The expansion of this pandemic was tackled by combining all the available resources and manufacturing processes. To this end, this paper proposed the development of a decision making framework that depends on the parameters that governs every time the situations.

In this work, the process time, the production volume, the flexibility in terms of processing different materials and the ramp up rate, were the main factors that were used as indicators for the process selection. By investigating the capabilities of each manufactuirng process, a hybrid manufacturing solutions was proposed. At the beginning of this effort, Glocal hubs were capable to produce, in very short time, low production volume in order to offer it to local hospitals. During this time, the industrial world was trying to adopt and transform the production lines in order to maximize the production of medical supplies, matching the demand. The combination of the aforementioned solutions with the aid of AM and IM processes, managed to provide enough equipment to cover the global needs for medical supplies in less time than applying each solution individually. However, this call to action was based on the individual companies' internal decision making policies and agenda, thus, a coherent and legislated framework is needed to secure the response in similar future crisis across the world.

As future research, the source of this shortage has to be studied in depth as well as to quantify how the individuals, the small enterprises and the industries managed to reach the desired production levels to counteract this shortage. Moreover, the way that Glocal Hubs were organized can be expanded and analyzed as a means to face similar crisis in the future. The modern means of communication, the automation technologies and the commercialization of AM seem capable to support similar reactions in the future. In Europe and in the Western world in general, the educational programs can adopt lessons that familiarize the young people and the individuals with modern technologies such as Additive Manufacturing, 3D design with Computer Aided Design (CAD) software, e-commerce, etc. that are fundamental for the requirements and the standrads of the modern world and they were crucial to overcome this difficult situation. If people understand and analyze what causes this unprecedented shortage of medical supplies, everyone will be better prepared to face a similar situation in the future, not only for medical supplies but for every kind of equipment. In terms of future technical developments, the manufacturing processes, regadless of the mechanism, ought to be improved in terms of flexibility, ramp-up time and production rate, so that manufacturing succeeds in safekeeping population through meeting demand for emergencies.

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References

Abid H., Mohd J. (2020). 3D printed medical parts with different materials using additive manufacturing. *Clinical Epidemiology and Global Health*, 8(1), 215-223.

Ahern J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning*, 100(4), 341-343.

Ball P., Roberts S., Natalicchio A., Scorzafave C. (2011). Modelling production ramp-up of engineering products. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 225.

Baumers M., Dickens P., Tuck C., Hague R. (2015). The cost of additive manufacturing: Machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change*, 102. 10.1016/j.techfore.2015.02.015.

Bessant J., Francis D., Meredith S., Kaplinsky R., Brown S. (2000). Developing manufacturing agility in SMEs. *International Journal of Manufacturing Technology and Management*, 2, 730-756. 10.1504/IJMTM.2000.001374.

Bikas H., Lianos A.K., Stavropoulos P. (2019). A design framework for additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 103, 3769-3783.

Bikas H., Stavropoulos P., Chryssolouris G. (2016). Additive manufacturing methods and modelling approaches: a critical review. *The International Journal of Advanced Manufacturing Technology*, 83(1), 389-405.

Cantrell J., Rohde S., Damiani D., Gurnani R., DiSandro L., Anton J., Young A., Jerez A., Steinbach D., Kroese C., Ifju P. (2017). Experimental Characterization of the Mechanical Properties of 3D Printed ABS and Polycarbonate Parts. *Advancement of Optical Methods in Experimental Mechanics*, 3, 89-105.

Carayannis E.G., von Zedtwitz M. (2005). Architecting gloCal (global–local), real-virtual incubator networks (G-RVINs) as catalysts and accelerators of entrepreneurship in transitioning and developing economies: lessons learned and best practices from current development and business incubation practices. *Technovation*, 25(2), 95-110.

Chartier Y. (Ed.). (2014). Safe management of wastes from health-care activities. World Health Organization.

Chryssolouris G. (2006). Manufacturing Systems: Theory and Practice, 2nd Edition.

Cook G.N. & Goodwin J. (2008). Airline Networks: A Comparison of Hub-and-Spoke and Point-to-Point Systems. *The Journal of Aviation/Aerospace Education & Research*. 17, 51-60. 10.15394/jaaer.2008.1443.

Coronavirus disease (COVID-19) pandemic, https://www.who.int/emergencies/diseases/novel-coronavirus-2019?gclid=CjwKCAjw9vn4BRBaEiwAh0muDE7Y_2M09VFXLj6I2Se3fCXbYsN6B1757eTmznJbrvrfZnOBLrUyhRoCAWEQAvD_BwE, Accessed 27/07/2020

Corporate Social Responsibility & Responsible Business Conduct, https://ec.europa.eu/growth/industry/sustainability/corporate-social-responsibility_en#:~:text=European%20Commission%20strategy%20on%20CSR,to%20international%20guidelines%20and%20principles.&text=The%20strategy%20also%20improves%20self,of%20social%20and%20environmental%20information, Accessed 27/07/2020

COVID-19 CORONAVIRUS PANDEMIC, https://www.worldometers.info/coronavirus/, Accessed 27/07/2020

Designs for Live-saving Breathing Aid to be Made Freely Available, https://www.mercedesamgf1.com/en/news/2020/04/ucl-uclh-f1-project-pitlane-start-delivery-breathing-aids-nhs-hospitals/, Accessed 27/07/2020

Douglas M.L., Cooper M.C. (2000). Issues in Supply Chain Management. *Industrial Marketing Management*, 29(1), 65-83.

Edition 2020, Covid Response, https://www.mvd.gr/, Accessed 27/07/2020

Edwards K.L. (2003). Designing of engineering components for optimal materials and manufacturing process utilisation. *Materials & Design*, 24(5), 355-366.

Elling R., Politis J. (1983). An evaluation of emergency medical technicians' ability to use manual ventilation devices. *Annals of Emergency Medicine*, 12(12), 765-768.

Fauci A. S., Lane H. C., Redfield R. R. (2020). Covid-19—navigating the uncharted. N Engl J Med, 382, 1268-1269

Fayezi S., Zutshi A., O'Loughlin A. (2017). Understanding and Development of Supply Chain Agility and Flexibility: A Structured Literature Review. *International Journal of Management Reviews*, 19, 379-407.

Ferrari. (2020). Ferrari continues its efforts to fight the Covid-19 pandemic, https://corporate.ferrari.com/en/ferrari-continues-its-efforts-fight-covid-19-pandemic, Accessed 27/07/2020

Gu X., Jin X., Ni J., Koren Y. (2015). Manufacturing system design for resilience. *Procedia Cirp*, 36, 135-140.

Guidance for wearing and removing personal protective equipment in healthcare settings for the care of patients with suspected or confirmed COVID-19, https://www.ecdc.europa.eu/en/publications-data/guidance-wearing-and-removing-personal-protective-equipment-healthcare-settings, Accessed 27/07/2020

Italian engineers support the fight against the COVID-19 virus by 3D printing valves to medical equipment, https://3dprintingcenter.net/2020/03/15/italians-support-the-fight-against-the-covid-19-virus-by-3d-printing-valves-to-medical-equipment/, Accessed 27/07/2020

Komineas G., Foteinopoulos P., Papacharalampopoulos A., Stavropoulos P. (2018). Build Time Estimation Models in Thermal Extrusion Additive Manufacturing Processes, *Procedia Manufacturing*, 21.

Kose H., Jin M., Peng T. (2020). Quality and productivity trade-off in powder-bed additive manufacturing. *Prog Addit Manuf,* 5, 199–210.

Leendert B.F. (1992). Manufacturing processes from an industrial management viewpoint. *Computer Integrated Manufacturing Systems*, 5(4), 269-275.

Li P., Xiao-Hui N., Hua L., Ning Z., Yan-Feng G., Fen P. (2020). Continuous positive airway pressure versus mandibular advancement device in the treatment of obstructive sleep apnea: a systematic review and meta-analysis. *Sleep Medicine*.

Mapping the auto manufacturers building PPE and medical equipment to battle COVID-19, https:\www.just-auto.com\analysis\mapping-the-auto-manufacturers-building-ppe-and-medical-equipment-to-battle-covid-19_id194945.aspx, Accessed 27/07/2020

Marti Pons-Òdena, Arnau Valls, Jordi Grifols, Ramon Farré, Francico Jose Cambra Lasosa, Bruce K. Rubin, (2020), COVID-19 and respiratory support devices, *Paediatric Respiratory Reviews*.

Mohd J., Abid H. (2018). Additive manufacturing applications in medical cases: A literature-based review. *Alexandria Journal of Medicine*, 54(4), 411-422.

Nesteruk I. (2020). Estimations of the coronavirus epidemic dynamics in South Korea with the use of SIR model.

Panoutsopoulos A. (2020). Known drugs and small molecules in the battle for COVID-19 treatment. Genes & Diseases.

Papacharalampopoulos A., Karapiperi A. and Stavropoulos P. (2020). Humanitarian engineering design methodology for AM metallic products: A smart mobility platform case, 8th CIRP Conference of Assembly Technology and Systems, 29 September to 1 October, Athens, Greece, pending publication in CIRP procedia

Papacharalampopoulos A., Giannoulis C., Stavropoulos P., Mourtzis D. (2020). A Digital Twin for Automated Root-Cause Search of Production Alarms Based on KPIs Aggregated from IoT. *Applied Sciences*. 10(7), 2377.

Partee B., Hollister S., Das S. (2006). Selective Laser Sintering Process Optimization for Layered Manufacturing of CAPA [sup ®] 6501 Polycaprolactone Bone Tissue Engineering Scaffolds. *Journal of Manufacturing Science and Engineering-transactions of The Asme*.

Pavan M., Todeschini R. (2009). 1.19 - Multicriteria Decision-Making Methods, Editor(s): Steven D. Brown, Romá Tauler, Beata Walczak,Comprehensive, Chemometrics, 591-629.

Peng T. (2016). Analysis of Energy Utilization in 3D Printing Processes. Procedia CIRP, 40, Pages 62-67.

Personal Protective Equipment (PPE), https://www.england.nhs.uk/coronavirus/secondary-care/prevention/personal-protective-equipment-ppe/, Accessed 27/07/2020

Shokrani A., Loukaides E. G., Edward E., Alexander J.G. Lunt, (2020). Exploration of alternative supply chains and distributed manufacturing in response to COVID-19; a case study of medical face shields. *Materials & Design*, 192, 108749.

Spinelli A., Pellino G. (2020). COVID-19 pandemic: perspectives on an unfolding crisis. *The British journal of surgery*.

Stavropoulos P., Foteinopoulos P. (2018). Modelling of Additive Manufacturing Processes: A Review and Classification. *Manufacturing Review*, 5(2), 8-34.

Tayler Y. (2016). Humanitarian engineering: innovative approaches and partnerships in crisis response. *MENA Knowledge and Learning Quick Notes Series*, 157.

Ti L.K., Ang L.S., Foong T.W. (2020). What we do when a COVID-19 patient needs an operation: operating room preparation and guidance. *J Can Anesth,* 67, 756–758.

Top German ventilator company warns on global supply crunch, https://www.ft.com/content/2f2845b3-a1ed-44cb-90af-e04d8d712403, Accessed 27/07/2020

Trappey C. V., Trappey A. J. C., Lin G. Y. P., Liu C. S., Lee W. T. (2007). Business and logistics hub integration to facilitate global supply chain linkage. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 221(7), 1221–1233.

Xi G., Xiaoning J., Jun N., Yoram K. (2015). Manufacturing System Design for Resilience, Procedia CIRP, 36, 135-140.

Yao W. (2020). Emergency tracheal intubation in 202 patients with COVID-19 in Wuhan, China: lessons learnt and international expert recommendations. *British Journal of Anaesthesia*.

Yildiz A., Ozerim M. (2014). Corporate Social Responsibility in European Context.

Zu Z. Y., Jiang M. D., Xu P. P., Chen W., Ni Q. Q., Lu G. M., Zhang L. J. (2020). Coronavirus disease 2019 (COVID-19): a perspective from China. *Radiology*, 200490.

3D CAD File: Respirator-free reanimation Venturi's valve, https://www.rs-online.com/designspark/3d-cad-file-respirator-free-reanimation-venturis-valve-jp , Accessed 27/07/2020