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Challenges in the Supply Chain for Personal Protective Equipment (PPE) during Covid-19

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ABSTRACT

The COVID-19 pandemic caused severe shortages of critical medical PPE products including gowns, masks, gloves, face shields, and N95 respirators. With the shortages in supply, hospitals and other healthcare providers as well as first responders experienced extremely high demand for PPE products. The radical increase in demand significantly impacted the supply chain network causing major shortages of supplies and disruptions in distribution.

The purpose of this paper is to understand the challenges faced in the US PPE supply chain during COVID-19 that resulted in severe PPE shortages across the country. By taking into consideration the many components involved in this complex topic, this paper aims to help readers understand the different factors that contributed to the collapse of the US PPE supply chain and also provide a deep discussion of the changes that are required to avoid similar situations to happen in the future.

The main objectives of this paper are:

- *Describe the main characteristics of PPE items, focusing on textile-based products*
- *Identify the challenges associated with PPE shortages in the US*
- *Recommend improvements to the PPE Supply Chain for COVID-19 and other pandemics*

This research paper is intended to provide valuable information that could both be used to improve the PPE supply chain in the current pandemic and to avoid the problems we have observed in the first six months of the current pandemic in future similar situations.

Keywords: Covid-19

Introduction

The COVID-19 pandemic faced the world to an unprecedented situation that disrupted the PPE supply chain in the US and produced massive PPE shortages across the country. Before heading to the COVID-related challenges, it is important to first understand

the functioning of the PPE supply chain in the US healthcare system. The distributors buy products from manufacturers or, in many instances, contract third parties to manufacture products, and then sell the products to the health care system. At present, US-based PPE production is limited, and more than 70% of respiratory protection supplies used in the US imported from China and other countries. With high global demand and drastically reduced production in China during early 2020, major distributors have been unable to fill orders. New suppliers and intermediaries have emerged in the PPE supply chain. Some health care systems have resorted to purchasing PPE from unvetted sources without the ability to fully evaluate supplier quality. Others have even created their own manufacturing facilities or partnered with local universities to meet serious shortages.

All supply chains are based on supply and demand, and this is true for PPE as well as for other products. When the demand for products changes rapidly and dramatically, the supply chain is stressed. Normally products are manufactured only in sufficient quantities to cover the anticipated normal demand, leaving little ability to increase production if needed (Patel et al., 2017). The current pandemic situation intensified those pre-existing issues. PPE shortages have been reported by mayors and healthcare leaders in many US cities, and this is also reflected in national surveys (Kamerow, 2020). There was a very rapid increase in the demand of PPE items, and with the existing characteristics of the US PPE supply chain, it became exceedingly difficult to get necessary PPE in quantities required to protect healthcare workers, first responders, and others.

With far more demand than supply, prices on these items increased rapidly, and also new organizations took this opportunity to start producing PPE but often at exorbitant prices. Many of these organizations, both manufacturers and distributors had no experience in producing and/or distributing these products. In addition, US PPE stockpiles originally created with the purpose of keeping a considerable inventory of items to supply healthcare workers in case of a public health crisis, were quickly exhausted. There was uncertainty and a lack of unified knowledge in sourcing for specific product components, testing requirements, and a lack of connection between product suppliers, needs, and the healthcare systems.

It was extremely difficult to accommodate the abrupt increases in the demand for critical products during a public health crisis like the current pandemic. In response to the considerable shortages of critical PPE items across the US during COVID-19, many different sectors of the textile industry and organizations made individual and collective efforts to help with the crisis. These organizations included INDA, IFAI, NCTO, SEAMS, THOMAS, Textile Connect, AAPN, #GetUsPPE, and Helena.org. They collaborated in many new ways to confront the PPE shortages. These efforts to connect the supply with the demand were often provided at no cost.

One of the pervasive challenges throughout this pandemic has been the lack of information. Data needed to understand what was needed, when, and where was often totally lacking or of extremely poor quality. Over six months into the pandemic, the Federal Government was still making changes to who was responsible for the data collection and analysis on even such basic information as number of cases, hospitalization, ICU utilization, and deaths (Davenport, Godfrey and Redman, 2020).

Many apparel companies quickly started producing masks and gowns and nonwoven companies retooled production facilities to manufacture the three-layer fabrics needed for N95 masks. Many companies who had not previously produced PPE, such as Ralph Lauren, Hanes, and Canada Goose started manufacturing and distributing PPE. The Nonwovens Institute (NWI) at North Carolina State University proactively

responded to the COVID-19 pandemic. The Institute quickly leveraged and modified its facilities to produce materials for the N95 respirators that are desperately needed in the coronavirus fight. The Nonwovens Institute focused its melt blown and spun bond nonwovens facilities and expertise to produce specially designed fabrics that were delivered to USA manufacturers to manufacture the respirators.

Many non-textile manufacturers, e.g., Ford and Honeywell, also responded to contribute in the manufacture of PPE. Many universities also responded to the current critical situation. Even though most universities suspended their normal operations in March, switching to an online format to protect students, professors and staff, some research laboratories remained open to assist with PPE supplies. Institutions around the country have worked hard in the past months to assist with the manufacture of materials required for the construction of PPE, to assemble finished products, or to produce innovative products and technologies as an alternative to the shortages of traditional PPE items.

This paper summarizes research done primarily by using the most updated information on the PPE supply chain based on research papers, industry websites, and newspaper articles. The novelty of this topic required the use of as many different sources of information as possible to properly illustrate the current situation.

Personal Protective Equipment (PPE)

According to the Occupational Safety and Health Administration (OSHA), Personal Protective Equipment (PPE) is defined as equipment that is worn with the objective of minimizing the exposure to hazardous substances. The, being most common items are gloves, foot and eye protection, protective hearing devices, hard hats, respirators, and full body suits (OSHA, 2004).

PPE is used by professionals in many different disciplines and plays a significant role in healthcare environments. Healthcare workers are frequently exposed to infectious agents and diseases during their daily activities. The use of PPE acts as a barrier between the individual and the infectious material and protects healthcare workers from disease transmission (CDC, 2004). These protective items have become even more important during the COVID-19 pandemic. Infection control tools and items like gloves, gowns, masks, respirators, googles, and face shields became critical products for healthcare settings. Table 1 shows the main characteristics of the most common types of PPE used in healthcare environments.

Table 1. Types of PPE used in healthcare environments (CDC, 2004) (OSHA, 2004)

Type of PPE	Protection purpose	Materials	Format
Masks	Protect mouth and nose	Nonwoven fabrics	Disposable
Respirators	Protect respiratory tract from airborne infectious agents	Nonwoven fabrics	Disposable
Gowns	Protect skin and/or clothing	Fabrics made of natural or manmade fibers	Reusable or disposable
Gloves	Protect hands	Vinyl, latex, nitrile	Reusable or disposable
Googles	Protect eyes	Plastic tight-fitting eye	Reusable

		protection	
Face shields	Protect face, mouth, nose, and eyes	Transparent sheets of plastic that extend from the eyebrows to below the chin	Reusable

This research has placed special attention on masks, respirators, and gowns due to their textile nature. Therefore, more detailed information will be provided on those items.

Masks

A face mask, also called surgical mask, is a medical device used to create a physical barrier between the face of the user (mouth and nose specifically) and possible droplets, splashes, sprays, or splatter that could contain germs such as viruses or bacteria (FDA, 2020). In the United States, this type of product must be regulated by the Food & Drug Administration (FDA) under 21 CFR 878.4040, and is classified according to ASTM standards that categorize masks into levels 1, 2, and 3, going from lowest to highest level of protection. The specified parameters for each mask level can be found in Table 2.

Table 2. Masks ASTM Standards (Primed, 2020) (Medline, 2009)

Criteria	ASTM Level I	ASTM Level II	ASTM Level III
Intended use	Procedures producing low amounts of fluids, spray and/or aerosols	Procedures producing light to moderate amounts of fluids, spray and/or aerosols	Procedures producing moderate to heavy amounts of fluids, spray and/or aerosols
BFE (Bacterial Filtration Efficiency) Against an aerosol containing 3.0 micron bacteria	≥ 95%	≥ 98%	≥ 98%
PFE (Particulate Filtration Efficiency) Against sub-micron particulate matter 0.1 microns in size	≥ 95%	≥ 98%	≥ 98%
Delta P (Differential Pressure): Air flow resistance (breathability) measured in mm H2O/cm2	< 4.0	< 5.0	< 5.0
Fluid Resistance to Synthetic Blood	80 mm Hg (venous pressure)	120 mm Hg (arterial pressure)	160 mm Hg (i.e. trauma/ orthopedic procedure pressure)
Flame Spread	Class 1	Class 1	Class 1

As indicated by the Food & Drug Administration, surgical masks are disposable devices that are not intended to be used more than once (FDA, 2020). Surgical masks have to be manufactured in waterproof materials in order to be protected from body fluids, and with materials containing a pore size which is small enough to filter 3.0 micron bacteria and 0.1 micron particulates such as viruses. Nonwoven Spunbond-Meltblown-Spunbond (SMS) structures have proven to meet these criteria effectively. The Meltblown middle layer, is usually from fine glasses or polymer fibers, and acts as a mechanical barrier that presents a microporous structure while being breathable (Ajmeri, 2011).

Even though surgical masks are effective medical devices that can block droplets, splashes, sprays or splatter that might contain harmful microorganisms such as viruses and bacteria, they don't provide complete protection from contaminants and small particles due to the loose fit present between the mask surface and the face of the wearer. From a product design perspective, the edges of surgical masks are not made to form a seal around the nose and the mouth, and this is the main difference between masks and N95 respirators which provide a complete seal in the face/mask interface (FDA, 2020).

Gowns

Medical gowns are used in healthcare environments for two main purposes. First, to protect the wearer from the spread of an infection or illness if the wearer comes in contact with infectious materials, and second to prevent the wearer from transferring harmful microorganisms (FDA, 2020).

The Food & Drug Administration (FDA) in compliance with the standard developed by the American National Standards Institute/Association of the Advancement of Medical Instrumentation (ANSI/AAMI) PB70:2012 titled "Liquid barrier performance and classification of protective apparel and drapes intended for use in health care facilities", recognizes four protection levels for gowns going from lowest to highest level of protection. The characteristics of each level can be found in Table 3.

Table 3. Gowns ANSI/AAMI standards (ANSI/AAMI, 2012) (FDA, 2020) (Ajmeri, 2011)

Criteria	**Level I** Minimal risk	**Level II** Low risk	**Level III** Moderate risk	**Level IV** High risk
Intended use	Basic care, standard isolation, cover gown for visitors, or standard medical unit	Blood draw, suturing, Intensive Care Unit, or pathology lab	Arterial blood draw, inserting an Intravenous line, Emergency Room, or trauma case	Long, fluid intense procedures, surgery, or pathogen resistance infectious diseases
AATCC-42 Water Resistance: Impact Penetration	≤ 4.5g	≤ 1.0g	≤ 1.0g	-
AATCC-127 Water Resistance: Hydrostatic Pressure	-	≥ 20cm	≥ 50cm	-

ASTM F1671 Viral Penetration	-	-	-	Pass
Types of materials	Lightweight spunbond PP and spunlace PET/Wood pulp	Medium weight SMS and spunlace PET/Wood pulp	Heavyweight SMS made out of three or more layers	Poly coated - made from SMS PP or spunlace PET/Wood pulp material coated with PE

Gowns are available as either reusable or disposable items. gowns can be made of cotton reusable materials or they can also be made of spun synthetic disposable materials (CDC, 2004).

For the reusable formats, one of the most typical textile constructions is a 50/50 polyester/cotton woven plied yarn fabric. Many coating and laminating technologies have been developed to impart fluid impermeable properties on these fabrics, such as Polytetrajuoroethylene (PTFE) microporous membranes or silicone and polyurethane coatings (Zins, 2011).

For the disposable formats, nonwovens materials are the most selected option. The most typical nonwoven constructions used for gowns can be found on Table 3. It can be seen that, as the level of the gown increases, usually the number of nonwoven layers increases in order to provide additional protection. For example, for level III gowns, Spunbond-Meltblown-Spunbond constructions of up to seven layers (SSMMMSS) are sometimes used. And, for level IV gowns, plasma treatments or antibiotic and fluorochemical treatments are sometimes selected to provide additional protection against blood, water, and microbes (Ajmeri, 2011).

Respirators

Respirators are devices designed to reduce exposure to airborne contaminants. There are many types of respirators depending on the end uses. For infection control purposes in healthcare, the most commonly used ones are Filtering Facepiece Respirators, also known as N95. A filtering Facepiece Respirator is a disposable device that filters out particles like dusts, mists, and fumes (CDC, 2018). Surgical N95 respirators are classified by the FDA as class II devices and are regulated by the FDA, under 21 CFR 878.4040, and CDC NIOSH under 42 CFR Part 84 (FDA, 2020).

The FDA defines N95 as a respiratory protective device that must be designed to achieve a very close facial fit and, therefore, provide very efficient filtration of airborne particles. This close facial fit is achieved by specially designing the edges of the respirator to form a seal around the nose and mouth (FDA, 2020). The 'N95' label means that, when the device is tested, it blocks at least 95 percent of particles 0.3 microns in size (FDA, 2020). In addition, the N states that the device is not resistant to oil, and within this category, and there are three levels of particle blocking: N-95, N-99, and N-100 (CDC, 2018).

Masks and respirators present many similarities in terms of the tests performed to evaluate their efficacy, since both are tested for bacterial filtration efficiency, particulate filtration efficiency, fluid resistance, flammability, and biocompatibility. Therefore, when it comes to desired manufacturing materials, nonwoven Spunbond-Meltblown-Spunbond (SMS) structures are the desired option for respirators as well.

Respirators should not be shared or reused, however, due to the increment in use of this device during COVID-19, the FDA issued an Emergency Use Authorization (EUA) that allows the use of decontamination systems

for certain respirators used by healthcare workers only if there are insufficient supplies of new respirators (FDA, 2020).

General considerations for the use of PPE
Selecting the right type of PPE depending on the intended use and anticipated level of exposure is just the first step towards a proper PPE infection control strategy. There are many aspects associated with the use of PPE that, if not taken into consideration, can greatly compromise the main end goal of this type of item which is to protect healthcare workers within healthcare settings, contributing to build a safe environment. Some of these key considerations include:

Fit
PPE items must present a perfect fit on the individual user, which most of the time is a healthcare worker (CDC, 2004). A perfect fit will not only provide the intended level of protection in the desired areas, but also it will increase the level of comfort of the healthcare worker while delivering health care.

Usage
According to the Centers for Disease Control and Prevention (CDC), special attention should be placed on how PPE is handled and discarded. Recommendations include putting on PPE before being in contact with the patient, and once the task is completed discarding the PPE item in a careful manner and discarding it in the dedicated area. Also, while PPE is being used, attention should be placed in limiting the amount and types of surfaces that are touched, since this can produce cross contamination in the environment (CDC, 2004).

Implications of PPE use during COVID-19
PPE is currently among the main approaches taken by countries around the world to limit and reduce the spread of COVID-19. The widespread use of these items, while providing numerous benefits already discussed in terms of protection and safety, has raised some concerns about the health impact that the PPE can cause on the user. Recent studies have shown that using PPE items for prolonged hours can cause serious skin irritations. As stated by Gheisari et. al., there is evidence of several skin reactions associated with the use of N95 respirators, such as acne, facial dermatitis, pigmentation, and urticarial facial eruption (Gheisari, 2020). Other authors have also studied PPE-associated headaches as a result of the combined use of N95 face masks together with protective eyewear like googles with a likelihood of developing headache pain when using both items together for periods of four hours or more (Ong, 2020).

Supply chain of PPE

The current COVID-19 pandemic is an unprecedented situation that disrupted the PPE supply chain in the US. One of the main characteristics of the supply chain of PPE in the US is that it is similar to many other goods based on the demand. Products are manufactured only in sufficient quantities to cover the anticipated normal demand, leaving little ability to increase production if needed (Patel, 2017). As a result, it becomes extremely difficult to accommodate abrupt increases in the demand, as would happen with a public health crisis like the current pandemic.

Data from the Association of the Nonwoven Fabrics Industry on PPE production before COVID-19 indicates that for the last three decades there has been an increased interest in relocating PPE production to China and other countries that offered extensive industrial capacities with lower costs. Also, efforts from hospital buyers were focusing almost exclusively on lowering the costs for critical equipment. This situation led to having between 50% to 80% of all the medical face masks used worldwide, as well as the majority of isolation/surgical gowns and other PPE items manufactured in China (Association of the Nonwoven Fabrics Industry, 2020).

In terms of local finished PPE production, Patel et. al. provides an estimation of the routine production worldwide of 1.5 billion

N95 respirators and 3.6 billion surgical masks produced annually (Patel, 2017). The Association of the Nonwoven Fabrics Industry also estimates that each month, the US produces 42 million N95 respirators and 16.6 million surgical masks (Association of the Nonwoven Fabrics Industry, 2020). One of the key materials used for PPE production is a meltblown nonwoven, and before the pandemic onset it was estimated that the meltblown demand to manufacture N95 respiratory masks and medical face mask equaled 4,500 tones, with 860 of those being supplied by the US (Association of the Nonwoven Fabrics Industry, 2020).

Supply Chain of PPE during public health emergencies

The manufacturing rates mentioned above can only be used as general estimations of the supply and demand under normal circumstances, however, public health emergencies like pandemics and epidemics present uncommon situations that are challenging to anticipate. A key component for the preparation of emergency situations is to analyze previous crisis situations and looking into the past, it is possible to find examples of public health emergencies that demanded an increase in the use of critical PPE items. In particular, the 2009 H1N1 influenza pandemic and 2014 Ebola virus epidemic represent interesting case studies that have been widely analyzed in the literature.

A publication by Patel et. al. analyzed the lessons learned from previous public health emergency responses regarding the use of PPE and concluded that it becomes challenging to make considerable increases in the supplies needed in case of an emergency without previously having advanced planning (Patel, 2017). As explained by the authors, during the 2009 H1N1 pandemic, there was a CDC recommendation for the use of respiratory protective devices that increased the demand for such items and while there was a release of N95 respirators and face masks from federal inventory, the items delivered to healthcare facilities were not the same items that healthcare workers had previously been fit tested and trained for, posing usability problems. In addition, there were issues related to the regulatory requirements by the FDA and the lack of federal guidelines for extended use and reuse of N95 respirators when the supply of these items was limited (Patel, 2017).

During the 2014 Ebola virus epidemic, as a result of the increased demand of PPE items, there was a proliferation of manufacturers and distributors that offered alternatives for some critical items in order to meet customer needs. However, most healthcare facilities were reluctant to opt for these alternative brands and models because their staff didn't have the required training and/or protocols set in place for these alternative products, which made the demand of certain product lines further exacerbated (Patel, 2017). Another important aspect from the Ebola epidemic mentioned by the authors was the successful coordination set in place between hospitals and states to share supplies. Partnerships among facilities allowed to better respond to increases in the demand and delays in the delivery of commercial products (Patel, 2017).

Other research, by Carias et. al, estimated the potential demand for N95 respirators and surgical masks in potential pandemic scenarios, using a Hypothetical Influenza Pandemic in the United States as an example and reached interesting findings. According to the estimations made in this study, in a scenario where 20% to 30% of the US population would potentially become ill, the demand for N95 respiratory masks for healthcare personnel and critical first responders would range between 1.7 to 7.3 billion depending on the severity/characteristics of the scenario, and the demand for surgical masks for suspected patients would be of 0.1 to 0.4 billion (Carias, 2015). Findings from this study indicate that current protocols and standards set in place for the interaction between healthcare workers and ill patients with respiratory

diseases might not be feasible during health emergency scenarios since they would require an impractical demand for critical PPE items. Also, authors point out that the minimal ability from the domestic respiratory device market to ramp up production, affected by availability of manufacturing capacity and raw materials, would create a large gap between the needed PPE items and the existent manufacturing capacity (Carais, 2015).

The Strategic National Stockpile (SNS)

Stockpiles in the US were created in 2002 through federal funding and initiatives related to the Public Health Security and Bioterrorism Preparedness and Response Act, with the purpose of keeping a considerable inventory of items that could properly supply healthcare workers, among other professionals, in case a public health event occurred. Over the years since its creation, this inventory of products started to include PPE items such as gloves and surgical gowns as a response to the PPE shortages observed by healthcare settings during both real and simulated public health emergencies and pandemics (Yorio, 2019).

Through the SNS history, one of the largest deployments of PPE items under public health emergency conditions was evidenced in 2009 during the H1N1 influenza pandemic, consisting of the distribution of 19.6 million pieces of PPE and 85.1 million N95 respirators across the US (Board on Health Sciences Policy, 2016).

While remaining definitely beneficial and vital for emergency responses, the SNS presents some challenges that need to be kept in mind. Storing such large quantities of PPE items can impact the aging and shelf life of such products. Most of the PPE items present in the SNS were purchased during some of the main public health events of the last decades, such as the severe acute respiratory syndrome (SARS) that occurred in 2003, the H1N1 influenza pandemic that took place in 2009-10, or the Ebola outbreak that occurred in 2014-15; and in some cases due to the considerable economic investments involved in purchasing and storing, items have been stored in a timeframe that is beyond the shelf life recommendations from the manufacturer (Yorio, 2019). There are shelf-life extension programs that bring solutions to this issue and are currently implemented for several stockpiled medical assets but, unfortunately, such programs do not exist for PPE items (Yorio, 2019). An alternative solution to this challenging situation would be to test the performance of beyond shelf-life items, however, this process not only becomes expensive but also most tests result destructive on the product, therefore, pose the risk of having an undesirable depletion of critical protective assets (Yorio, 2019). Handfield et al. have carefully reviewed the current situation of the US Strategic National Stockpile and made several recommendations for major changes in the SNS (Handfield, et al., 2020).

For the above reasons, the use of federal resources during public health emergencies, while beneficial, shouldn't be chosen as the main and only approach. Instead, authors like Patel et.al. and Handfield et al. recommend the development of strategic plans that could be integrated seamlessly in the supply chain, using resources from both the federal SNS and the PPE manufacturing commercial system, and considering important aspects like the quality of products needed, the characteristics of the storage space required for such products, and the most appropriate product rotation system to keep inventories relevant (Patel, 2017).

Issues with the Supply Chain of PPE during COVID-19

The challenges and limitations of the US Supply Chain for PPE before COVID-19 was discussed in the previous section and after analyzing the lessons learned from previous public health emergencies, the US would be expected to have a better sense of readiness and proper strategic plans in place. Unfortunately, that was not the case and the current pandemic situation did nothing but intensify those pre-existing issues.

In March 2020, at the onset of the COVID-19 pandemic in the US, PPE shortages started to be reported in national surveys with the news that close to one third of the healthcare facilities were nearly out of face masks by March 27th, and 13% and 25% of the institutions surveyed reported being out of plastic face shields and gowns respectively (Kamerow, 2020). Mayors from several cities also reported a similar alarming situation, and from the 213 mayors that responded to a national survey, 91% reported having insufficient supplies of face masks and, what was even more alarming, 88% communicated that they did not have sufficient PPE items for their healthcare workers and first responders (Kamerow, 2020).

Naturally, COVID-19 had different effects across the US and, consequently, PPE shortages had different effects on each state. While hospitals in big cities like New York were among the most affected ones experiencing hard difficulties with keeping sufficient supplies to respond to their increased PPE demand; other smaller cities didn't experience such critical situations due to their lower pandemic burden (Kamerow, 2020).

There was a very rapid increase in the demand of PPE items, and with the characteristics of the US PPE Supply Chain, it became very difficult to get needed supplies. In addition, prices on these items increased rapidly, and also new dealers took this opportunity to start producing PPE but offering exacerbated prices and demonstrated no competence in producing this type of equipment. The Strategic National Stockpile became one of the available pathways for the acquisition of the needed PPE items, but the request response varied through the country. While states like Florida successfully got all the supplies requested, other requests were not met, with areas like New York and New Jersey receiving just a portion of what was initially requested as a result of the federal government not having enough PPE existing in the SNS able to satisfy demands from all states (Kamerow, 2020).

Several areas of the US, as well as many countries around the globe started to enter into what is defined by the CDC as crisis mode in order to optimize the use of face masks (Livingston, 2020). According to CDC guidance, health systems that enter into a crisis mode are advised to make changes in their normal operations in order to preserve the use of critical PPE items. These changes include: cancelling all those non urgent procedures and patient appointments that would require the use of face masks, extending the use of face masks beyond the original manufacturers shelf life recommendations, and prioritizing the use of face masks to those activities with high occurrence of splashes, sprays, and/or aerosolization (Livingston, 2020). During this crisis scenario, many hospitals have reported implementing even more drastic and alternative solutions, like replacing traditional PPE items with domestic products such as plastic garbage bags to counteract the lack of gowns, or plastic water bottles cutouts to provide eye protection (Livingston, 2020).

It is difficult to determine what is the origin of the issues experienced with shortages, since many different factors are involved in the conversation. Consequently, lack of sufficient protection items is not only a result of an increase in the demand and an unprepared supply chain, but also inappropriate use of protective equipment needs to be considered. There is a wide agreement worldwide from international organizations that the use of PPE in an appropriate manner considerably decreases the risk of viral transmission and infection. As a result, PPE guidelines and recommendations from such entities are usually consistent in their main principles. However, PPE use is not consistent through different healthcare institutions or states, and this lack of consistency can lead to a misuse or overuse of PPE that ultimately will have a negative effect on stockpiles and pose an increased risk to healthcare workers and patients (Cook, 2020).

US response to PPE shortages

In response to the considerable shortages of critical PPE items across the US during COVID-19, many companies, organizations, and academic centers made individual and collective efforts to help with the crisis. In the following sections, some of the many examples available will be described.

Industry

The first response to the PPE shortages, as expected, came directly from the industry sector. Small, medium and large companies realized that there was a need for critical protective equipment, and quickly identified which of their resources could become useful to ramp up production of PPE components and/or finished goods. These efforts not only allowed companies to collaborate with the worldwide crisis, but also resulted in an efficient way of keeping the jobs of employees that would have been laid off otherwise, and in some cases opened the door to new business opportunities.

Textile/Apparel companies

US Textile and Apparel companies helped meet PPE shortages by increasing manufacture of finished PPE and healthcare products. Some companies were fortunate to have existing lines of production that were already focused on the PPE field prior to the pandemic or suited for that purpose with minor changes. LA Corp, a cut and sew manufacturer based in Lebanon, VA, rapidly developed a special supply chain to manufacture medical face masks, pivoting 90% of their production to PPE items (SEAMS, 2020). Other companies were not able to provide finished products but increased the production of valuable components needed to make PPE, such as yarns, thread, fabrics, elastic, and antibacterial and durable water repellent finishes for reusable items. Contempora Fabrics, a knitting company based in NC, began producing over 200,000 yards of fabric weekly in order to provide textile material with water repellent and antimicrobial finishes used for masks and gowns (SEAMS, 2020).

Contempora Fabrics efforts were part of a bigger coalition of American apparel brands and textile companies led by yarn supplier Parkdale Inc. that was created in March 2020 with the purpose of creating a medical face mask supply chain to assist hospitals, healthcare workers, and citizens (NCTO, 2020). Another example of collective efforts was created by the Carolina Textile District (CTD) as part of their COVID Response activities. In a short period of time, the CTD was able to create a network of more than 60 manufacturers to source and test fabric, create PPE patterns for mass mask production, and turn existing lines of production to masks and other PPE items. By working two shifts daily, this initiative allowed the production of 40,000 masks a week, and it is estimated that to date, more than 500,000 units of masks and gowns have been produced, with 5,554 of those being donated (Carolina Textile District, 2020).

Table 4. Industry Response

Textile/Machinery Companies				
Company	**Location**	**Field**	**Covid response**	**Source**
Costwold Industries	New York	Technical textiles and engineered fabrics	Adapted their commercial workwear products to PPE production Developed an isolation gown made from 100 percent recycled plastic bottles	Steele, 2020
Kamber Narrow Fabric Machinery	Birmingham, AL	Fabric Machinery	Helped companies pivoting to PPE: Created a rental program to help with the investment required with machinery purchase Built custom looms configured to PPE in less than two weeks	Steele, 2020
Textile Technology Center	Belmont, NC	Testing, Prototyping and Production	Developed new PPE testing, production, and prototyping services	Steele, 2020
TREX Machine Group	Charlotte NC	Knitting Machine Supplier	Pivoted from machinery and equipment supplier to PPE manufacturer Developed knitted neck gaiters and face masks containing DuPont Silvadur™ antibacterial agent	Steele, 2020
Milliken	Spartanburg, SC	Materials science	Increased inventory of reusable fabrics used for PPE, distributing more than 10 million yards since March Scaled up production of antimicrobial Biosmart fabric	Milliken, 2020
Henderson Sewing Machine Co.	Andalusia, AL	Supplier of Industrial Sewing Machines	Introduction of new automated systems to produce pleated, foldable and cup-type face masks Introduction of semi-automated systems to manufacture other PPE items	SEAMS, 2020
HomTex Inc.	Vinemont, AL	Contract manufacturer of sheeting	Shifted to the production of cotton face masks for business and individuals Launched new PPE brand “Sovereign America” that commercializes 3-ply disposable masks	SEAMS, 2020 - Sovereign America, 2020

Most of the initiatives previously mentioned were developed at the onset of the pandemic in the US, as a response for the abrupt demand for PPE items. However, some companies are expecting a sustained demand for PPE in the longer term, and as a response are developing strategies to create bigger scale projects. The Fallon Company and Shawmut Corporation have teamed up together to set up a new N95 Mask manufacturing facility that is expected to allow the end-to-end production of up to 180 million masks annually, and also creating over 300 new jobs. This initiative is being possible through the support of a $2.7 million grant from the Commonwealth's Manufacturing Emergency Response Team (MERT) (Globe Newswire, 2020).

In some cases, PPE shortages also led the way to product innovations much needed in the protective equipment field. Some companies identified areas of improvement in terms of material development and product design, and consequently, developed PPE items that not only provided protection against the virus, but also had an added benefit to the final user. A great example of this can be found through the copper-infused, antimicrobial, washable masks with added moisturizing Shea Butter developed by Nufabrx to help combat the mask related acne that regular face masks generate on the skin of some users. Nufabrx company, originally focused on pain-relieving socks, compression garments, gloves, and workout clothes has had such a success with the shea butter infused masks that had to hire 12 new employees and is currently considering switching to mask production on a permanent basis (Annable, 2020).

Designer and apparel brands in higher product categories traditionally dedicated to the production of fashionable apparel and non-PPE items also responded by manufacturing protective items. Designer Christian Siriano, with his team of 10 seamstresses, dedicated full time to mask production, an initiative that was also followed by Michael Costello and Karla Colletto labels (Segran, 2020). Hedley & Bennett, originally dedicated to the design and manufacture of high-end aprons, also started to produce masks that even though are not medical grade and not appropriate for healthcare workers, are designed to protect employees that still need to interact with other individuals on a daily basis through lower risk situations, for example in warehouses or commercial kitchen environments (Segran, 2020). These efforts, while not directly oriented to healthcare workers and healthcare facilities, are designed to offer alternative solutions to low risk general users and also to save high quality N95 and surgical masks to the professionals who really need them.

Non-textile companies

Massive PPE shortages in the US called for significant efforts from every part of the manufacturing industry, and companies outside of the textile and apparel fields were able to considerably collaborate too. The first step was to identify which of the company's available resources could be suitable for PPE production, and consequently learn how to manufacture the most needed PPE items.

The controlled environment clean rooms commonly found on automotive manufacturing facilities resulted particularly beneficial for the safe production of face masks for medical use, turning the automotive industry in one of the key non-textile industries to aid in PPE manufacturing. An interesting example of this can be seen in the efforts from Ford Motor Company, that aided in the manufacture of reusable gowns produced using airbag materials, and also in the production of more than 650,000 N95 respiratory masks as part of a partnership with Gore & Associates, just to name some of the many initiatives by the company (Ford, 2020).

Honeywell is another great example of a company outside of the apparel and textile realm that provided valuable knowledge in engineered materials and useful

manufacturing capabilities to help in PPE production. In order to help to address the increased demand for protective items, Honeywell started a hard and steady journey in April by setting up new N95 mask production lines at several US locations. Initially, the production capability consisted of 20 million masks a month, and with sustained efforts production capability energetically increased through the year, reaching a considerable milestone at the end of 2020 with the delivery of more than 225 million face masks in the month of December (Honeywell, 2021).

The role of Organizations and Academia

As previously discussed, the efforts of manufacturers from both textile/apparel and non-textile fields became critical to aid in the production of thousands of PPE across the country to protect healthcare workers, first responders, and patients. However, there is still another important factor worth mentioning in this story, and that is the outstanding work made by Organizations and Academia, which will be explained in the following sections.

Organizations sharing resources

At the beginning of the COVID-19 pandemic in the US, it became clear that the country was entering into a critical situation that would require considerable work and efforts from many sectors of the society. As discussed, PPE shortages became one of the the main issues, but there were many other co-related challenges. Even though many manufacturers started producing PPE, there was a big gap and miscommunication between the supply and demand of those items: healthcare facilities were in desperate need of protective items but were not properly in contact with new suppliers. Also, textile, apparel, and automotive companies switching to the production of PPE were facing many issues in discovering the best practices for the production of a new type of product for them, and they had to do that in a timely manner to be able to help with the crisis.

Textile, Apparel, and Healthcare organizations soon realized that they had valuable resources and networks big enough to act as resource centers to connect the supply with the demand and provide online free resources for the manufacture of PPE, with the ultimate goal of helping to improve the PPE shortages situation. Some examples of these efforts include the creation of manufacturers databases, the collection of information about possible donations, and the development of online Resource Hubs with valuable information for the design, development and manufacturing of PPE. These resources included: guidelines and parameters for each type of PPE, patterns and sewing instructions, and directories of the most appropriate textile materials, among many others.

One of the main initiatives worth describing in detail was the “Textile-related Supply & PPE Supplier Directory" developed as a collective effort between the Industrial Fabrics Association International (IFAI), the National Council of Textile Organizations (NCTO), and the Association of the Nonwoven Fabrics Industry (INDA). This directory was developed using information from surveys made to IFAI, NCTO, and INDA members at the beginning of the pandemic with the purpose of identifying potential suppliers for PPE that could offer the much-needed help to fill the national healthcare protective items demands (IFAI, 2020). The resulting online document is divided into three categories: finished goods, with suppliers that can make ready to use products fully sewn or assembled; inputs, with suppliers that can provide vital materials required for manufacturing finished PPE, such as fibers, resins, nonwovens, knit/woven fabrics, and yarns; and services, including all the suppliers capable of providing cut & sew operations and machinery (IFAI, 2020). Table 5 provides a summary of the main Organizations and their COVID-19 response efforts.

Table 5. Efforts from Organizations

Organization	Field	COVID response	Source
IFAI **Industrial Fabrics Association International**	Member-owned, member-driven trade association representing the global industrial fabrics industry	**COVID-19 Resource Center**	IFAI, 2020
		Supplier Directory	
		Patterns and Resources	
		Government and agency information	
		Financial information and assistance	
		Textile industry updates and news	
		IFAI member updates	
		Products, Services, and Equipment	
		Training and conferences	
		Sourcing questions and opportunities	
NCTO **National Council of Textile Organizations**	Association representing the entire spectrum of the textile sector.	**COVID-19 Response**	NCTO, 2020
		Resources for procuring medical supplies and PPE	
		Resources & Support for PPE Conversion for All Manufacturers	
		To sell medical supplies or equipment to the federal government	
		To donate medical supplies or equipment to FEMA	
		CDC product specifications	
		Textile Industry PPE Response Blog Coverage	

SEAMS	The Association of the US sewn products industry	SEAMS PPE Pattern Resource HUB	SEAMS, 2020
		SEAMS Power Search System	
THOMAS	Industrial sourcing platform and marketing powerhouse	**Thomas COVID-19 Resource Hub**	THOMAS, 2020
		Find COVID-19 Response Suppliers	
		Become a COVID-19 Response Supplier	
Textile Connect	Collaborative website designed to connect textile complex companies, events, resources, product and market information	Database of companies in the Medical/Hygiene field	Textile Connect, 2020
AAPN **Americas Apparel Producer's Network**	Apparel factory association	AAPN Fireside Chat with Industry Members about the pandemic takeaways	AAPN, 2020
		AAPN Resource Sheet	
		AAPN Members Pivot to PPE Videos	
#GetUsPPE	National nonprofit organization that obtains PPE via donations and makers, and delivers it to under-resourced facilities	Request PPE	GetUsPPE, 2020
		Give PPE	
		Make PPE	
Helena	COVID-19 Response Project	The COVID Network	Helena, 2020

Academia driving technological innovation

The COVID-19 pandemic disrupted many activities and industry, and this was also the case of education centers and universities. Due to the pandemic in the US, almost every university had to suspend the usual operations in March right in the middle of Spring Semesters. This meant switching to an online format and closing most of the onsite facilities. However, some research laboratories soon realized that they had valuable R&D resources that could provide innovative solutions to the PPE shortages observed through the country.

For this task, many resources became useful. Some research groups assisted with the manufacture of materials required for the

construction of PPE and in some cases even assembling and delivering finished goods. A great example of this can be found in the efforts made by the Nonwovens Institute (NWI) at North Carolina State University. Nonwoven materials are the core component of many PPE items, especially when it comes to the much needed N95 respiratory masks. Through research, the Nonwovens Institute was able to create a new spunbond material with effective filtering properties without needing to use the traditional meltblown layer typically used for filtration systems and managed to produce 2,000 meters of this innovative material per hour, estimated to reach quantities of 20,000 per hour in the future (Kulikowski, 2020). In addition, the NWI announced a partnership with Blue Cross and Blue Shield of North Carolina (Blue Cross NC), Freudenberg Performance Materials, UNC Health, the NC Healthcare Association and NC Medical Society with the objective of producing N95 respirators, starting with 100,00 to 200,000 units per month, and with strong plans to quickly increase the production capacity in the future (High, 2020).

Other research groups focused on the development of innovative products and technologies that could be used as alternative strategies to the shortages of traditional PPE items. Among many examples available in the recent literature on the topic, the innovative use of 3D printing technologies was at the forefront of diverse projects, such as: the modification of arthroplasty helmets to serve as PPE by researchers at Duke University (Erickson, 2020), and the development of 3D printed face shields by researchers at the University of Michigan (McAlpine, 2020). Some researchers also focused on the creation of solutions for the disinfection of PPE to turn disposable items into reusable alternatives. An example of this work was a project from researchers at Michigan Technological University that had the goal of developing a scalable sanitation system for hospitals leading to developing a prototype consisting of a mobile unit that uses heat to sanitize PPE (Mills, 2020).

Discussion

After having dedicated previous sections to the explanation of the characteristics of the Supply Chain in the US, the disruption in PPE resources due to COVID-19, and the subsequent response from Industry manufacturing PPE, organizations providing collective resources, and academia driving material development and innovation, it becomes important to leave place for a final discussion on the complexity of this topic that might result useful for similar future scenarios.

What could have been done differently?

The fact that COVID-19 pandemic is an unprecedented situation makes it challenging to have strategic plans set in advance. However, when comparing the PPE supply chain issues faced during previous public health emergencies such as the 2009 H1N1 influenza pandemic and 2014 Ebola virus epidemic with the supply chain issues related to the current pandemic, many similarities seem obvious. Therefore, it seems reasonable to think that many of the strategies already outlined from the lessons learned from previous crisis scenarios could have been used in the current scenario.

In particular, after looking into the many components that led to the current PPE shortage crisis, it can be concluded that the following theory developed by Patel et. al. (2017) on the publication titled "Personal Protective Equipment Supply Chain: Lessons Learned from Recent Public Health Emergency Responses" could have been of great use during the current scenario:

> "The focus on preparedness over the past decade has been on products (e.g., drugs, vaccines, devices, and diagnostic tools). Although these products are extremely important, recent events emphasize that the ''system'' for product manufacturing, distribution of supplies, and product use is critical to the success of a response. Building system capacity and private and public sector partnerships

will help improve agility in the system, resulting in a more effective, organized emergency response." (p. 250)

Efforts towards the remaining period of COVID-19

Even by the time this research is published, the COVID-19 pandemic is still a local and global concern with affected patients all over the world. New updates on the topic also indicate that PPE shortages are still occurring in many healthcare facilities across the country. Therefore, there is much work still to be done for the remaining duration of the pandemic.

One of the areas that needs to be addressed is trying to find answers to the questions that still remain unanswered about what is the most appropriate way of designing, handling and using textile-based PPE items. Due to the novelty of this virus, review reports and high quality evidence are limited and more studies should be conducted in order to have solid evidence about the following topics outlined by Cook (2020) in the publication titled "Personal protective equipment during the coronavirus disease (COVID) 2019 pandemic – a narrative reviewL" In which scenarios/activities is it better to use one type of mask over another? What are the effects of decontaminating and reusing N95 masks in terms of mask effectiveness and material properties?

Another area that still needs to evolve without a doubt is the US Supply Chain of PPE items. In addition to the initiatives already mentioned, the industry, organizations, and academia are still working to find alternative solutions. One of the latest efforts worth mentioning is being made by the National Council of Textile Organizations (NCTO) led by Kim Glas through some of the following initiatives: develop a strong plan to address legislative issues associated with the manufacture and purchase of PPE, continuing the work towards getting long term contracts that would make PPE production investments more attractive, continuing current communications with hospitals and distributors to generate a better engagement on current PPE supply chain issues (Steele, 2020).

Things to consider for future pandemics

As it occurred with the lessons learned from the 2009 H1N1 influenza pandemic and 2014 Ebola virus epidemic public health emergencies, it is likely that the current COVID-19 pandemic will leave behind a series of valuable lessons to keep in mind in case similar conditions arose in the future. After analyzing the many players involved in this complex topic, it is recommended that future efforts should focus on two main areas: development of strong PPE supply chain systems and performing extensive R&D to improve current PPE textile-based items. The recommendations of Handfield et al. and others to rethink the US Strategic National Stockpile should also be a priority of the US Administration and Congress.

Having such a strong dependence on outsourced PPE items has proven to be problematic during the global crisis, and it has also been proven that local supply chains of products with such a high degree of technical/healthcare-related components cannot be created overnight. Therefore, in order to better adapt to future pandemic situations, strong efforts should be put in place right now in order to create a stronger local PPE US supply chain with strong focus in both the processes required to manufacture protective equipment and the raw materials required to manufacture such items.

While a stronger local supply chain is being built, parallel efforts should be made in the R&D field. The extensive use of textile-based PPE items during the pandemic has highlighted the urgent need for finding alternative PPE reusable items to decrease the incredible waste generated by disposable items. Research conducted at universities with the help of industry partners has the potential to lead to more sustainable and effective alternatives to protect healthcare workers and patients from pathogenic

microorganisms while resulting in less damage to the environment. Also, the prolonged use of protective systems for several hours, especially as it routinely happens with healthcare workers and first responders, has brought to attention the high number of skin reactions and headaches associated with their use. Therefore, it is also important to conduct research on the materials, designs, and protocols associated with the use of PPE items to turn such products into more comfortable and safe items.

Conclusion

The COVID-19 pandemic disrupted every aspect of what was considered normality, and after analyzing the many components involved in the current PPE shortages experienced in the US, it is possible to reach the following main conclusions.

Lessons learned from previous public health emergencies, in addition to previous theories about the lack of a strong and reliable US PPE supply chain were reinforced by the recent series of events. And taking this idea into an even further perspective, most countries throughout the world identified a high dependence on PPE items manufactured in China.

This pandemic proved that collective, generous, and honest work can lead to great results, which can be observed analyzing the recent individual and collective efforts made by textile, apparel, and non-textile companies. During the current crisis, it was not only about competition or purely making good business decisions, rather than that, focus was placed on helping the healthcare workers and care providers.

Last, this pandemic highlighted that, while industry and manufacturing are very important components of a supply chain, organizations, new projects, and even small research projects can also lead to great developments and innovations. Therefore, it becomes important to improve the communication between each player and work towards a unified goal attacking the issue from different and diverse fronts.

References

AAPN. (2020). *Americas Apparel Producer's Network*. Retrieved December 26, 2021, from https://aapn.memberclicks.net/

Ajmeri, J. R. (2011). Nonwoven materials and technologies for medical applications. In V. T. Bartels (Ed.). *Handbook of medical textiles* (pp. 106-131). Cambridge, UK: Woodhead Publishing Limited.

American National Standards Institute/Association of the Advancement of Medical Instrumentation (ANSI/AAMI). (2012). *Liquid barrier performance and classification of protective apparel and drapes intended for use in health care facilities (Standard No. PB70:2012)*. Retrieved May 13, 2020, from http://my.aami.org/aamiresources/previewfiles/PB70_1206_preview.pdf

Annable, V. (July 24, 2020). North Carolina company's new masks get the attention of the federal government. *The News & Observer*. Retrieved May 23, 2020, from https://www.newsobserver.com/news/coronavirus/article244402067.html

Association of the Nonwoven Fabrics Industry, INDA. (2020). *Meltblown Nonwoven Markets: COVID-19 Impact Analysis*. Retrieved December 26, 2021, https://www.inda.org/meltblown-nonwovens-markets-covid-19-impact-analysis/

Board on Health Sciences Policy; Health and Medicine Division; National Academies of Sciences, Engineering, and Medicine. (Oct. 24, 2016). *The Nation's Medical Countermeasure Stockpile: Opportunities to Improve the Efficiency, Effectiveness, and Sustainability of the CDC Strategic National Stockpile: Workshop Summary. 2, The Strategic National Stockpile: Origin, Policy Foundations, and Federal Context*. Washington (DC): National Academies Press (US). Retrieved May 23, from https://www.ncbi.nlm.nih.gov/books/NBK396378/

Carias, C., Rainisch, G., Shankar, M., Adhikari, B. B., Swerdlow, D. L., Bower, W. A., Pillai, S. K., Meltzer, M. I., & Koonin, L. M. (2015). Potential demand for respirators and surgical masks during a hypothetical influenza pandemic in the United States. *Clinical infectious diseases: an official publication of the Infectious Diseases Society of America, 60 Suppl 1(Suppl 1)*, S42–S51. https://doi.org/10.1093/cid/civ141

Carolina Textile District. (2020). *Covid Response*. Retrieved December 16, 2020, from https://www.carolinatextiledistrict.com/covid-response

Centers for Disease Control and Prevention (CDC). (June, 2004). *Guidance for the Selection and Use of Personal Protective Equipment (PPE) in Healthcare Settings*. Retrieved August 20, 2020, from https://www.cdc.gov/hai/pdfs/ppe/ppeslides6-29-04.pdf

Centers for Disease Control and Prevention (CDC). (Jan., 2018). *Respirators*. Retrieved August 15, 2020, from https://www.cdc.gov/niosh/topics/respirators/

Cook, T. M. (2020). Personal protective equipment during the coronaviru disease (COVID) 2019 pandemic – a narrative. *Anaesthesia*, 75, 920–927. https://doi.org/10.1111/anae.15071

Davenport, Thomas H.; A. Blanton Godfrey and Thomas C. Redman (Aug. 25, 2020). To Fight Pandemics, We Need Better Data. *Sloan Management Review*. Retrieved September 15, 2020, from https://sloanreview.mit.edu/article/to-fight-pandemics-we-need-better-data/

Erickson, M. M., Richardson, E. S., Hernandez, N. M., Bobbert, D. W., 2nd, Gall, K., & Fearis, P. (2020). Helmet Modification to PPE With 3D Printing During the COVID-19 Pandemic at Duke University Medical Center: A Novel Technique. *The Journal of arthroplasty*, 35(7S), S23–S27. https://doi.org/10.1016/j.arth.2020.04.035

Food & Drug Administration (FDA). (Feb., 2020). *Personal Protective Equipment for Infection Contro*l. Retrieved August 15, 2020, from https://www.fda.gov/medical-devices/general-hospital-devices-and-supplies/personal-protective-equipment-infection-control

Ford. (Apr. 13, 2020). *Ford to produce respirators, masks for COVID-19 protection in Michigan*. Retrieved December 16, 2020, from https://corporate.ford.com/articles/products/ford-producing-respirators-and-masks-for-covid-19-protection.html

GetUsPPE. (2020). *Get Us PPE Homepage*. Retrieved December 26, 2021, from https://getusppe.org/

Gheisari, M., Araghi, F., Moravvej, H., Tabary, M. Dadkhahfar, S. [Letter to the editor]. (Apr. 17, 2020). Skin reactions to non-glove personal protective equipment: an emerging issue in the COVID-19 pandemic. *Journal of The European Academy of Dermatology and Venereology*, pp. 297-298. https://doi.org/10.1111/jdv.16492

Globe Newswire. (Oct. 15, 2020). *Fallon and Shawmut Team Up to Create New N95 Mask Production Facility in Massachusetts to Meet Sustained Demand for PPE*. Retrieved December 16, 2020, from https://www.wicz.com/story/42772184/fallon-and-shawmut-team-up-to-create-new-n95-mask-production-facility-in-massachusetts-to-meet-sustained-demand-for-ppe

Handfield, Robert; Daniel Joseph Finkenstadt; Eugene S. Schneller; A. Blanton Godfrey; and Peter Guinto (2020), "A Commons for a Supply Chain in the Post-COVID-19 Era: The Case for a Reformed Strategic National Stockpile," *Milbank Quarterly*, Vol. 98, No. 4, pp. 1058-1090.

Helena. (2020). *COVID-19 Response.* Retrieved December 26, 2021, from https://helena.org/projects/covid-19-response

High, M. (Sept. 28, 2020). P*ublic and Private Partners Join Forces to Deliver PPE to Health Care Workers Statewide — All Made in NC*. Retrieved December 16, 2020, from https://news.ncsu.edu/2020/09/made-in-nc-partners-deliver-ppe-to-health-care-workers/

Honeywell. (Jan. 11, 2021). *Honeywell Delivers 225 Million N95 and Surgical Masks in December for Health Care and Government Use*. Retrieved January 25, 2021, from https://www.honeywell.com/us/en/press/2021/1/honeywell-delivers-225-million-n95-and-surgical-masks-in-decembe

IFAI. (2020). *IFAI's COVID-19 Resource Center*. Retrieved December 26, 2021, from https://www.ifai.com/covid-19/

Kamerow D. (2020). Covid-19: the crisis of personal protective equipment in the US. *BMJ (Clinical research ed.), 369*, m1367. https://doi.org/10.1136/bmj.m1367

Kulikowski, M. (Apr. 2, 2020). *A Necessary Filter: Nonwovens Institute Steps Up to Combat COVID-19*. Retrieved December 16, 2020, from https://news.ncsu.edu/2020/04/a-necessary-filter/

Livingston, E., Desai, A., Berkwits, M. (Mar. 28, 2020). Sourcing Personal Protective Equipment During the COVID-19 Pandemic. *JAMA The Journal of the American Medical Association*, 323(19). https://doi.org/10.1001/jama.2020.5317

McAlpine, K. (Apr. 23, 2020). *U-M-approved face shield design guides makers addressing the PPE shortage through 3D printing*. Retrieved December 16, 2020, from https://news.engin.umich.edu/2020/04/u-m-approved-face-shield-design-guides-makers-addressing-the-ppe-crisis/

Medline. (2019). *Face masks, eyewear and N95 respirators*. Retrieved August 10, 2020, from https://www.medline.com/media/catalog/Docs/MKT/LITe19034_BRO_Surgical%20Face%20Masks_19.pdf

Milliken. (Apr. 2, 2020). *Milliken pivots textile manufacturing to produce advanced medical PPE*. Retrieved August 10, 2020, from http://milliken.com/news-overview/press-releases/milliken-pivots-textile-manufacturing

Milliken. (July 27, 2020). *Milliken & Company increases inventory of reusable protective medical fabrics ideal for PPE*. Retrieved August 10, 2020, from http://milliken.com/news-overview/press-releases/milliken-increases-medical-fabrics-inventory

Mills, A. (Apr. 08, 2020). *MTU Engineers Build Mobile Unit to Clean COVID-19 PPE*. Retrieved December 16, 2020, from https://www.mtu.edu/news/stories/2020/april/mtu-engineers-build-mobile-unit-to-clean-covid19-ppe.html

National Council of Textile Organizations (NCTO). (Mar. 21, 2020). *Coalition Of Iconic American Apparel Brands & Textile Companies Heeds Call Of Nation To Produce Medical Face Masks*. Retrieved June 15, 2020, from https://www.textileworld.com/textile-world/2020/03/coalition-of-iconic-american-apparel-brands-textile-companies-heeds-call-of-nation-to-produce-medical-face-masks/

National Council of Textile Organizations (NCTO). (2020). *COVID-19 Response*. Retrieved December 26, 2021, from http://www.ncto.org/federal-government-covid-19-procurement/

Occupational Safety and Health Administration (OSHA). (2004). *Personal Protective Equipment*. Retrieved August 15, 2020, from https://www.osha.gov/Publications/osha3151.pdf

Ong, J., Bharatendu, C., Goh, Y., Tang, J., Sooi, K., Tan, Y. L., Tan, B., Teoh, H. L., Ong, S. T., Allen, D. M., & Sharma, V. K. (2020). Headaches Associated With Personal Protective Equipment - A Cross-Sectional Study Among Frontline Healthcare Workers During COVID-19. *Headache, 60*(5), 864–877. https://doi.org/10.1111/head.13811

Patel, A., D'Alessandro, M. M., Ireland, K. J., Burel, W. G., Wencil, E. B., & Rasmussen, S. A. (2017). Personal Protective Equipment Supply Chain: Lessons Learned from Recent Public Health Emergency Responses. *Health security, 15(3)*, 244–252. https://doi.org/10.1089/hs.2016.0129

Primed Medical Products. (2020). *Clinical Resources*. Retrieved August 30, 2020, from https://www.primed.ca/clinical-resources/

SEAMS. (2020). *SEAMS PPE Pattern Resource Hub*. Retrieved June 15, 2020, from https://seams.org/ppe-patterns/

SEAMS. (May, 2020). *SEAMS PPE Special Edition*. Retrieved June 15, 2020, from https://www.slideshare.net/NancyKinderknecht/seams-ppe-special-edition-236000291

Segran, E. (Mar. 23, 2020). How your business can help fight coronavirus: One brand's pivot to making masks. *Fast Company*. Retrieved from https://www.fastcompany.com/90480732/this-high-end-apron-company-switched-to-manufacturing-masks-in-24-hours

Sovereign America. (2020). *About Us*. Retrieved December 16, 2020, from https://sovereignamerica.com/pages/about-us

Steele, D. (Oct. 22, 2020). *Coping with COVID: Textile companies, suppliers forge ahead while dealing with pandemic*. Retrieved October 30, 2020, from https://www.etextilecommunications.com/102220

Steele, D. (Oct. 15, 2020). *NCTO's Glas talks U.S.-made PPE, raises caution flag on other issues*. Retrieved October 30, 2020, from https://www.etextilecommunications.com/101520-ncto-glas-fall-meeting

Textile Connect. (2020). *Medical/Hygiene Industry Category Search*. Retrieved June 15, 2020, from https://www.textileconnect.com/search?naics=423450,339112,622110,339113,313230,313221

THOMAS. (2020). *Thomas COVID-19 Resource Hub*. Retrieved June 15, 2020, from https://help.thomasnet.com/covid-19-resource-hub/?navsource=ssra

Vordos, N., Gkika, D. A., Maliaris, G., Tilkeridis, K. E., Antoniou, A., Bandekas, D. V., & Ch Mitropoulos, A. (2020). How 3D printing and social media tackles the PPE shortage during Covid - 19 pandemic. *Safety science*, 130, 104870. https://doi.org/10.1016/j.ssci.2020.104870

Yorio, P. L., Rottach, D. R., & Dubaniewicz, M. (2019). Quality Assurance Sampling Plans in US Stockpiles for Personal Protective Equipment. *Health security*, 17(2), 140–151. https://doi.org/10.1089/hs.2018.0133

Zins, H. M. (2011). Reusable medical textiles. In V. T. Bartels (Ed.). *Handbook of medical textiles* (pp. 80-105). Cambridge, UK: Woodhead Publishing Limited.