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Adapting to Slow-Moving Crises: The Personal Protection Equipment Supply Chain in the Time of COVID19

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ABSTRACT
In this paper, we look at the supply chain for PPE during the COVID-19 pandemic of 2020. We look at the way the supply chain has responded to the pandemic, the coordination of the supply chain relative to the needs of primary users, and the consequences of its use. We find that the supply chain has continued to function more as a commercial supply chain than as an emergency supply chain largely because of a lack of centralized coordination. We include an analysis of existing concepts as they apply to this supply chain, but also incorporate preliminary results from a series of interviews with key players in this and related supply chains.

INTRODUCTION

This year, the personal protective equipment industry (PPE) wound up not only in a pandemic, but also in a political storm. In ordinary times, competitors have straightforward supply chains. For example, N95 masks require only a few raw materials to manufacture: rubber for the strap, polypropylene for the mask, and metal or staples to attach the strap to the mask. These materials are readily available in the United States and internationally due to the economic contraction caused by the pandemic. Other uses for these materials have diminished, so these materials have in some ways become more available.(Manfredi, L., 2020, May, 3; O'Brien, J., 2020, March 23).

But these are not ordinary times. While raw materials are available, healthcare professionals have faced shortages of PPE, in some cases with probably tragic results. Major firms have attempted to adapt to new conditions, but without centralized coordination, these adaptations have only been partially successful. The major companies typically use distributors for finished products instead of direct shipping to individual customers. 3M, a major competitor in the PPE industry, has chosen to move to direct shipping to customers during the pandemic to speed the process and cut down on price gouging by distributors (Manfredi, L., 2020, May, 3; O'Brien, J., 2020, March 23).

Given these circumstances, several questions arise. What is the nature of the disruption to the PPE supply chain? What can be done to avoid such disruptions in the future? What plans might improve the effectiveness of such supply chains for future crises? The supply chain in most industries have been disrupted during the current pandemic, but few have been more visible than the PPE. It is important to analyze what has worked well and where companies could improve during this pandemic and in potential future pandemics. It also becomes important to sort out the political from the practical.

Another issue is the difference between commercial supply chains and humanitarian supply chains. Related to that is the issue of slow-moving versus fast-moving disasters and the supply chains appropriate to them. We will not attempt in this paper to deal with all of them, but touch

on key issues related to them, using the PPE industry as an example. We should also point out that we have used qualitative data in our results, but data collection is on-going, so any conclusions that we draw must be considered preliminary.

This paper is arranged into three sections. The first section is a literature review on supply chains in general and on the ideas expressed in the literature apply to the PPE supply chain. It includes brief discussions of the article, its application to PPE, and some interview results from an ongoing study. The interview results are presented anonymously at this time because the data have not been fully analyzed. The second section discusses more broadly how theories in supply chain management and the preliminary study results apply to the PPE industry. The third section draws conclusions and calls for further research in this arena.

LITERATURE REVIEW

In some regards, this literature review is a review of supply chain literature reviews. It touches on the literature in purchasing, inventory control, warehouse location, supply chain network design, transportation, and warehouse operations. We start with purchasing.

Purchasing, Logistics, and the PPE Supply Chain

Fabbe-Costes & Nollet (2015) showed how logistics and purchasing are interdependent departments, and how treating them as such benefits the company. Through a literature review and comparison, they discuss how seeing them as interdependent improves the management of the supply chain. This collaboration, commonly known as supply chain integration, starts as an internal process and then is extended to external processes. Although these are closely related functions, the authors found that little research had been done regarding the internal integration of the departments (Fabbe-Costes & Nollet, 2015).

Fabbe-Costes & Nollet (2015) examined two organizational functions in their research, logistics and purchasing. They reviewed the historical growth of each field, seeking four things: 1) the strategic objective of the function; 2) how the function was viewed by management; 3) which aspect of managing the function fulfilled: and 4) how much of the function was outsourced.. They found that logistics evolved from simply controlling costs in the 1970s to resiliency and sustainability most recently.

Purchasing evolved in the same period from supporting management to contributing strategically or being outsourced.They attribute the rapid growth in logistics to computing power that has allowed for advanced modeling. They concluded that the two departments need to collaborate and communicate to improve supply chain management overall.

Discussion and Results

For PPE in this crisis, the integration of these two functions was intriguing. First, the crisis put purchasing functions in firms from outside the PPE supply chain in the position of attempting to purchase PPE or related materials.One of our interview subjects, for example, described the purchasing and logistics problem for a meat processing plant. Meat processing plants needed to buy protective equipment of a nature and quantity that they did not understand. These were experienced purchasing professionals, but they were in no position to understand how and when to source PPE, how to judge its quality, or how to store it.

According to this interview source, a large meat processing plant faced exactly this problem. They were offered a wide variety of masks and other PPE, but had no way of evaluating the supplier, the quality of the product, or the appropriateness of the product for their needs. Furthermore, they were being offered masks and gloves in quantities that belied storage--some would be suppliers were offering disposable masks in quantities of billions. This meant coordinating with logistics to determine what was doable.

As it happened, the supplier making such an offer was illegitimate, someone who had no access to such quantities, but such fake suppliers slipped in opportunistically and caused much confusion in this market. Fortunately, in the case of this meat packer, they sought help from an expert in PPE who was able to sort the problem out for them, at least to some extent. Of course, this did not involve the supply chain for standard, medical PPE.

Inventory Control and the PPE Supply Chain

Jackson, Tolujevs, and Kegenbekov (2020) studied past and current inventory control models. They started by differentiating between analytical and non-analytical approaches to inventory control. They included analytic models from as far back as 1888. The analytic model, the EOQ, is particularly suited to a single product that is robust to violations of specific assumptions. Since many products today will not fit these assumptions, this model has major drawbacks, although it remains in use in many computer systems.

They examined non-analytic models that included control theory, dynamic programming, simulation optimization, and metamodeling. Control theory uses differential equations to create a model that more closely mirrors real-world conditions. This theory also works best with a single product. The dynamic programming approach can be used with multiple products in a stochastic environment. Simply put, approximations are made to come to an optimal model for inventory control. Simulation-based optimization is conducted by algorithms that attempt to create optimal solutions based on inputs. The metamodel, or model of models (Jackson, Tolujevs, & Kegenbekov, 2020), utilizes models that have worked satisfactorily in other simulations.

Discussion and Results

Many of these models struggle to meet the conditions produced by a pandemic. While some are dynamic and adaptive, the variations fall outside the range of tolerable variation for the models. Not only that, but the existence of false offerings and shifting orders mean that the models work well for the information they have, but that information is often wrong. PPE orders were delayed. Shipments were shifted to other destinations without notice. Information on availability was incorrect. Prices fluctuated in unpredictable ways, but primarily went up. This kind of information disruption damages the ability of models to function and to provide good information for decision making.

Many of the difficulties in managing PPE inventory in these circumstances arose because the models work well when information is sound. One of our informants told us about receiving orders from six different representatives of one state for the same shipment of PPE. The state was effectively competing with itself for the goods, not to mention other states and the federal government. Inventory rarely sat in the distribution centers or warehouses in the early days of

this process, so much of the inventory was in transit. The PPE manufacturers experienced little of the inventory carrying costs, however, because payment was often in advance. The value of the inventory changed in two ways. First, the cost rose for additional capacity that was less suited for the manufacture and prices of raw materials rose. Second, the prices for PPE rose as the perceived shortage pushed buyers to raise their bids.

Transportation and the PPE Supply Chain

Transportation mode and carrier choice continue to be the most important transportation decisions a supply chain manager makes. Meixell & Norbis (2008) industry challenges such as capacity shortfalls, changing fuel prices, capacity shortages, environmental issues, international growth, and security concerns. Their discussion was based on an extensive literature review (Meixell & Norbis, 2008). They considered only the literature published after deregulation in 1980.

They found that carrier choice decisions were based on three main characteristics: carrier attributes; shipper decision processes; and integration of shipper and carrier into the shipper's supply chain. They also found that most shippers consider customer service more important than costs, but costs rated second. If shippers seek long-term relationships with carriers, then they tend to stress to the carrier the attributes that they seek, usually details related to service levels. These details will vary by customer. Four general models summarized the shipper decision making processes: an economic model,an inventory-theoretic model, a trade-off model, and an optimization model (Meixell & Norbis, 2008). Integration covered matters like which ports a carrier served, shipment size, segments in the transport chain, and warehousing throughout the transportation chain.

The authors list six significant findings from the literature review: 1) Attributes of the carrier are important to the customer; 2) Choosing the carrier and mode are "multi-attribute" (p. 202) problems; 3) Changes in regulation and the market have changed the attributes that are important to customers; 4) capacity of the carriers and the industries has been well covered in research: 5) surveys and mathematical modelling is widely used in choosing carriers and modes of transportation; and 6) supply chain integration has allowed customers more flexibility and shipping options.

Gorman, et al. (2014) investigated the ways modes of transportation used operations research (OR) and management science (MS) to improve the efficiency and lower the costs of moving goods. Freight transportation is a large part of the world economy (over 3% US GDP) . Because freight "transportation is asset, labor, and fuel intensive" (Gorman & et al., 2014, p. 535), managing the costs involved becomes more complex as the network grows.

Gorman, et al. (2014) looked at six freight operations: ocean, air, rail, truck, truck-rail intermodal, and package delivery. They discussed five areas of interest in each operation; network design and management, mobile asset planning and management, terminal management, load management, and unique areas of research.

Carriers must consider two main factors when developing networks, designing the network with appropriate routes and scheduling efficiently. The authors point out that speed of freight

transportation isn't always the most efficient since going faster requires more fuel (Gorman, et al., 2014). Carriers must balance the design of the fleet between fleet size and type of vehicle. Managing mobile assets (vehicles) and the terminals (vehicles, freight, labor) efficiently can have immediate effects on the cost of moving freight. Returning empty vehicles from one port drives costs higher with no corresponding income. Managing loads can make or break a transportation operation.

Some areas suggested for research are using game theory to model pooling fleets to increase flexibility, using OR modeling to help rail companies manage congestion and capacity, using OR modeling to help less-than-truckload (LTL) carriers manage uncertainty, and using similar pricing processes for freight as airlines use for passengers. The authors conclude that scheduling is one area in need of research in any transportation mode. Since all of the transportation modes have more information than ever before, OR modeling can assist with turning that information into knowledge.

Discussion and Results

Since supply chains were often disrupted for PPE, it's no surprise that transportation experienced some disruptions like rerouting, but such disruptions in transportation and transportation decision making were relatively few. Truck driver turnover remained much higher than in the Great Recession when it fell to 39%. In the pandemic, the turnover rate rarely fell below 80% and has returned to near 100% as of this writing. This suggests the skewed nature of the economic effects of the pandemic to date. A majority of Americans still have enough income to keep buying and to draw trucks into service. Driver turnover remains a capacity issue, but most trucking firms have operated without buying new trucks during this period.

Some of the trucking capacity has turned to the delivery of PPE, but still more of that capacity continues to operate in routes that serve their traditional customers. For example, dedicated auto haulers are operating at 80% of their normal capacity.

Since all modes of transportation have been used at some point in PPE supply chains, all of the techniques discussed could be used in this situation. It again depends on the accuracy of the information that goes into the models and how the models inform decisions.

For example, one of our interview subjects was directly involved in shipping PPE and medical equipment by air from the US to China in early February. When this became public knowledge, it created some controversy. The shipment and its arrangements were attributed to President Donald Trump and the White House in political ads, but that attribution was debunked by the Washington Post fact checking operation. That operation found that President Trump and the White House had nothing to do with arranging or authorizing the shipment (Kessler, April 22, 2020). The shipment was arranged by Project Hope, a charity that had worked in Wuhan for more than 25 years. The people who arranged and delivered the shipment had no idea that any controversy would be involved.

Network Design and the PPE Supply Chain

Onstein, Tavasszy, and van Damme (2019) reviewed the literature on the design of transportation and distribution networks in a global context. Several designs have prevailed for

decades: direct from the manufacturer to the store or consumer; through multiple layers of distributors in multiple countries, including domestic and international distribution; and hybrids of the two. Cross-docking also aids international distribution.

Good logistics networks address four main purposes: meeting customer service needs, reducing logistics costs, adapting to rapid changes in material needs, and making informed financial decisions. Onstein, Tavasszy, & van Damme (2019) found little research describing the factors that companies use to determine optimal logistics models. The literature in their review fell into three main categories: supply chain management, transportation, and geography.

When managers used a supply chain management perspective to choose locations for distribution centers, they tended to focus on demand characteristics, logistics service levels and costs, and product characteristics. When they used a transportation perspective, they concentrated on optimization models with the goal of reducing logistics costs. When they took the geographic perspective, they focused on accessibility, land and labor costs, and contextual factors including taxes and labor laws (Onstein, Tavasszy, & van Damme, 2019).

This research found that while many factors are considered in choosing locations in transportation networks, little research links these factors to how companies ultimately determine locations. They suggest studying the relationship among factors and decisions, determining a way to integrate factors from different approaches to research, and investigating "logistics sprawl" (Onstein, Tavasszy, & van Damme, 2019, p. 257).

Discussion and Results

For PPE, the networks function well in ordinary times. They adapted poorly to the initial surge in demand for additional PPE, to the detriment of healthcare workers in the first U.S. hotspots like New York and New Jersey. This was not the fault of the routine, existing supply chains for PPE. Rather, it was a consequence of chaotic responses from government entities, including states and the federal government. The network was there, but the supply was not directed toward the points of need. The manufacturers had adequate networks, but no sense of direction and no access to abundant global supply.

In our interviews, one informant said flatly that globally there was never a shortage of PPE. Not only were the materials available, they were abundant. At one point, as a supplier of PPE, she received six orders from agents representing one state, but all six were for the same supply requirement. This clearly had nothing to with the PPE network operated by manufacturers like 3M. So network design was not at fault. Rather, it was directing supply to the network.

Warehousing and the PPE Supply Chain

It is not sufficient to simply place a PPE distribution center. Rather, it must also be operated. One of the most important operations in a warehouse is order picking. Altarazi & Ammouri (2018) simulated ways to order pick manually. Since manual order picking requires careful planning to protect supplier and customer relations, the plan must be well thought out and attainable. The results of the simulations show layouts and warehouse sizes that are mostly likely to work best.

While manual order picking is common in warehousing, it is also labor intensive. Human interaction is required at every step from receiving the merchandise to picking merchandise and shipping it out. Warehouse designs typically start with analytical methods that follow the process sequence in the warehouse. Policies are often determined after these details have been determined (Altarazi & Ammouri, 2018). Simulations allow for policies to be set first, followed by laying out detailed processes.

In the past, researchers have used discrete event simulation and agent-based modeling, usually to study five common operational policies: strict order, batch, sequential zone, concurrent zone, and wave picking (Altarazi & Ammouri, 2018), all patterns for picking merchandise. The studies then considered how to minimize distance traveled by machines and staff and ways to maximize the utilization of equipment.

In their simulations, the authors examined five main warehousing design decisions: throughput, size, layout, operational policies, number of carts, and number of staff (Altarazi & Ammouri, 2018). They began the simulation with some defined independent variables like a rectangular warehouse and statistical data for certain warehousing functions such as receiving time, unloading time, and shipping times. They studied different layouts to determine the most effective layout and policies.

They used ARENA, a simulation software, to develop modules that worked together to form the larger simulation. The first part of the simulation described the incoming freight process that included receiving, unloading, and stocking shelves. The second part of the simulation measured the outgoing freight processes. Statistical data was developed using ANOVA and Tukey's multi-comparison tests. They used sensitivity analysis on the number and types of products (SKUs).

Ultimately, Altarazi & Ammouri (2018) suggest several areas for research based on the following results: 1) horizontal layouts are preferred to other layouts; 2) small warehouses are preferable, but larger warehouses can be broken down into smaller segments; 3) adding an aisle to the rectangular layout adds efficiency as opposed to changing the layout; 4) high throughput is more efficient in small warehouses; and 5) compromises must be made between the number of SKUs in a warehouse and the time it takes to handle each SKU.

Discussion and Results

Warehouses for PPE suffered from both shortages and backups during the early days of the pandemic. Like other businesses, they had employees who were out sick, stayed away for safety, or were laid off. The legitimate sellers of PPE continued to operate in much the fashion they had before the crisis, but with more production capacity dedicated to PPE when it was possible. They may have been slow to respond because they lacked clear direction. This is one of the areas where the commercial supply chain differed from the humanitarian supply chain. In effect, someone needs to direct a commercial supply chain to become part of an humanitarian supply chain when that is not a normal part of business.

Warehouse operations change little in terms of processes. They were too busy to make major changes. Also, their operations remained largely normal because they were never called into the

humanitarian supply chain. The allocation of inventory followed the ordinary processes of going to those who paid for them and directed their course. This included most states individually, the federal government, hospital and other medical systems, and large companies who were still feeling their way through the purchasing processes.
Our interview subjects discussed having to change operations in their warehouses to accommodate customers whose businesses were growing--like PPE producers--and to vacate space allocated to those with declining businesses. The pandemic was determinate.

Customer Service and PPE Supply Chains

In rapid-onset emergencies like hurricanes, cost considerations in customer service are often abandoned in favor of service. In the pandemic, customer service seemed to take on both a short-term and a slow-developing humanitarian caste, as well as some business as usual. Naoui (2014) used qualitative analysis to present an integrated approach to customer service performance and management. He found that as customer behavior changed globally, the costs of fast delivery needed to be controlled. Other aspects of the supply chain need to be considered in developing customer service procedures. Some items to consider are accurate, timely deliveries, flexibility, responsiveness, and relationship (Naoui, 2014). Customer service is broken down into pre-transactional, transactional, and post-transaction elements such as customer service policies, out-of-stock levels, and guarantee/repair, respectively.

Utilizing a case study of Alpha, a telecommunications enterprise, Naoui (2014) interviewed employees that had direct contact with customers to determine how employees feel they are doing with customers. Questions included ideas about what supply chain management is, how does customer service fit into the supply chain, how is your customer service, and the roles of several systems within the supply chain (IT, expertise, etc.). Naoui (2014) was able to build a framework for customer service within Alpha that could be used to conduct further, in-depth research about customer service in supply chain management.

All aspects of daily life have been affected by rapidly changing information and communication technology (ICT) (Zhou & Piramuthu, 2012). These changes have benefits and pitfalls that may not always be anticipated. The problem of ethics is compounded by the fact that technology can be utilized to conduct immoral or illegal activity with less chance of being caught. The authors begin with a literature review about business ethics and new technologies and then investigate ways in which RFID technology has benefited supply chain management and the dangers of using the technology.

Discussion and Results

Customer service has obviously been less than perfect for PPE in the pandemic. Shortages matter locally, not globally. Our informants tell us that the supply is available globally, but individual healthcare workers in the U.S. have done without PPE, worked with makeshift PPE, or used the same PPE for far longer than designed. Multiple sources report fatalities among healthcare workers that might be associated with a lack of PPE or lack of adequate PPE.

Still, the routine supply chains operated in routine fashion, just as many other supply chains did. These supply chains suffered no more disruption than others in terms of illness among workers or supply disruptions. They may even have escaped with fewer such disruptions.

ETHICS AND PPE SUPPLY CHAINS

Zhou & Piramanthu (2012) integrate the study of ethics with the choice of technologies and regulations that a company should develop. By deciding ahead of time how customer and business partner information will be handled within the company and possibly outside the company, a company can provide assurances to other companies that the information will be safe or reveal that the information will be shared.

When deciding if a technology meets the ethical standards of a company, several things must be considered such as company values, customer expectations, legislation, and cultural and social values. Ultimately, the social consequence of technology should be considered. RFID tags were seen as a tool to track shipments and verify that the product was handled within certain parameters (temperature, tipping over, etc.), but it was found that competitors could potentially "listen" to the RFID tags to learn about the supply chain of its competitors.

Zhou & Piramanthu (2012) use a matrix referred to as the Technology Regulation Development (TRD). The matrix lists all considerations to analyze before choosing a new technology. It guides ethical decision making as it clearly outlines expectations of the company and outcomes that benefit the company. Utilizing the TRD matrix, the authors argue that the benefits of using RFID tags do not outweigh the potential harm they could cause.

Discussion and Results

The technology decision tells only part of the ethical circumstances of PPE supply chains in the pandemic, but it does provide a starting point. Tracking and tracing are important to making sure that an adequate supply reaches the chosen destination in the right condition, for example. But the disruptions in the supply chain and the potential for national as well as local 'selfish' behavior put ethical considerations at the forefront of this crisis. Who should get PPE? Who should get it first? Where should it be made? What suppliers are available? All of these questions arose early in the crisis, though based on our contacts and interviews, the shortage was more perceived than real and remains so.

It is clearly unethical for faux suppliers to attempt to collect deposits on non-existent stock and dysfunctional if not unethical for government entities to dispatch multiple agents in pursuit of the same order. The ethical circumstances surrounding PPE, both conventional and ad hoc, will become clearer with time. At the moment, the preliminary results in the US seem disappointing.

HUMANITARIAN AND COMMERCIAL PPE SUPPLY CHAINS

According to the literature, humanitarian disasters have three attributes that influence the design of response supply chains: 1) occurrence in time and space; 2) system disruption; and 3) overwhelmed capabilities (Mackay, Munoz, & Pepper, 2019). The dimensions that affect humanitarian supply chain design are the time horizon, spatial concentration, affected population needs, perceived probability of occurrence, and perceived probability of consequence (Mackay, Munoz, and Pepper, 2019). The key distinction between commercial and humanitarian supply chains remains the profit motive.

In supply chain research, we have seen that service often outweighs cost, but this is magnified in the face of disasters. Reach the people who need the goods and services; ignore the costs to the extent possible. This was apparent in the private sector response to Hurricane Katrina. Southern Companies put getting the electric grid turned back on above the cost of doing so, bringing the grid back up for most people in less than ten days.

Still, humanitarian disasters of all types challenge supply chains and especially supply chain design. Even stable humanitarian supply chains sometime defy modeling, although modeling has been shown to be useful in most circumstances (Blecken, Hellingrath, Dangelmaier, & Schultz, 2009)

Discussion and Results

As is often the case, the COVID-19 pandemic response has been confused and confusing. Disasters often are unexpected, although not necessarily unanticipated. Countries can prepare forthem even when they do not know when they will arrive. Private firms have adapted in many ways to the pandemic. Manufacturers of toilet paper shifted parts of their supply chains from commercial institutional products to commercial home products, for example.

The response in the PPE supply chain has been mixed in the U.S. In one instance, a manufacturerof hospital masks contacted the federal government about raising production levels. He was ignored, so he maintained production at 600,000 units a week, although his capacity would allowfor up to 3 million units. There remains a shortage of N95 masks based on a recent survey of 21,500 nurses and healthcare workers (Anderson, 9/23/2020).

According to the *Washington Post*, N95 masks are still in shortage for six reasons:

1. The government hasn't used the Defense Production Act on N95 masks the same way it did on ventilators. Instead, it allowed manufacturers to scale up as they saw fitand didn't fund potential new manufacturers.

2. Many hospitals cut costs by using medical supply companies to provide equipmenton an as-needed basis rather than creating a stockpile of personal protective equipment, as they knew that the government had the strategic national stockpile filled with PPE it could rely on. But the H1N1 flu epidemic in 2009 depleted 85 million N95s from the stockpile, and the supply was never replenished.

3. HHS funded the invention of a machine that could make 1.5 million N95 masks perday, but when the design was completed in 2018, the government didn't purchase it.

4. HHS turned down an offer in January from a manufacturer that could have made millions of N95 masks. The agency didn't start ordering the masks from multiple companies until March 21, when the U.S. had 8,000 reported COVID-19 cases, andhealthcare workers were already worried about PPE shortages.

5. Without long-term guarantees that the government will keep buying respirators, N95manufacturers are wary of investing too much to boost production.

"It is not profitable to make respirators in the United States," Peter Tsai, a scientistwho invented a method to charge the fibers inside the N95 mask's filter, told the *Post*.

6. U.S. N95 makers have protected their processes as intellectual property, declining toshare information with other companies that could start making the masks, too." (Anderson, 2020, p.1)

Ethics probably suggest that political considerations should never come into play during a pandemic, but that's not what has happened. For the most part, the PPE producers have stayed out of the conversation. Their commercial supply chains continue to function as described in the*Post* article.

DISCUSSION

PPE supply chains became the source of political controversy at times, but most of that has settled down. The controversy around the 17 ton shipment to Wuhan has faded, having been awarded two Pinocchios by Washington Post fact-checkers (Kesslert, 2020). While the lack of centralized coordination was certainly a problem, not just because of its absence at that time, but also because states were not warned that the disaster response would be their responsibility, the claim noted here was falsely attributed to the President.

This reflects the politicization of issues related to the pandemic and to the responses to it. The traditional PPE supply chain suffered from some disorganization and some issues, particularly in trying to determine its role as either a commercial or a humanitarian supply chain. The crisis also spawned a related cottage industry for face coverings, face coverings that do not meet medical standards and emphatically do not meet N95 standards. However, these masks have also come to symbolize a political divide in the U.S. These have nothing to with the existing supply chains for PPE, but they have arisen beside it.

The functions of logistics and purchasing are significant in the current pandemic for all PPE. Companies manufacturing and distributing PPE must understand where the products are needed, how many are needed, and how to distribute them in a way that helps the most people. The United States was unable to buy the product from American companies initially, but after considerable bad press, they began selling to the US government and hospitals within the US. These companies had to balance purchasing and logistics with profit and how the public viewed them. The Anderson (2020) article describes the industry situation.

Where PPE is concerned, 2020 has proven that inventory needs can be unpredictable. It is likely that the simulation-based optimization model would have worked well pre-pandemic when demand was stable. Post-pandemic pandemic models will have to account for the movement of demand as the pandemic shifts around the country and the world. The dynamic programming model has been shown to work well with the irregularities like those seen with the pandemic. However, the models will likely need to change as the pandemic subsides.

PPE carrier and mode choices were likely much simpler before February 2020. Once COVID-19 struck, the need for PPE throughout the world changed the landscape for moving PPE. Any company looking to ship COVID-19 supplies likely will receive assistance within the United States with the federal government being a customer and distributor. That this became somewhat confused and distorted is problematic. It requires further study. PPE companies must currently decide on carriers and modes of transportation based on rate and shipping times with less emphasis on other attributes such as environmental effects or security concerns. A question remains about the urgency of such shipments, as well as precisely where they need to go.

3M, like any other PPE producer, must consider all the items discussed here. Since 3M already has a seemingly well-designed logistics network, it has been able to deliver the product to its

distributors effectively. Had there not been an effective network already in place, 3M would have to adapt to the pandemic and adjust the network to include additional outside storage and/or transportation to and from the additional centers. 3M did begin to distribute masks directly to medical facilities and governmental agencies, eliminating the distribution centers. All manufacturers of PPE must consider the needs of the population in the US and internationally which will affect any decision about distribution centers.

Because of the high throughput that personal protective equipment manufacturers are trying to accommodate, creating a simulation to streamline manufacturing processes should be considered. The fastest-moving SKUs should be moved closest to the receiving and freight areas to save time by minimizing travel time and staff time. If the manufacturers already have simulation models in place, they can use them to rethink the layout of the warehouse and placement of freight. If they do not already have a simulation model built, it would probably be in their best interest to begin developing a model for future use. The needs of the world can change overnight as we have seen with COVID, and these companies must be able to adapt with little warning.

This article applies in many ways to the PPE field. Since PPE is in such high demand, manufacturers, distributors, and customers must make a trade-off between speed and cost. Ocean travel is not a feasible option for the items most needed such as masks and gowns but could still be used for large shipments of other types of PPE. Air, rail, and truck seem to be the best option for shipping at this point. This type of network design should already be in place for emergencies. 3M did have a plan in place to distribute the products, but it simply could not keep up with demand. Having a good relationship with specific carriers before an emergency can lead to priority treatment during an emergency.

Companies in the PPE field need to consider how their customer service departments are reacting to the pandemic. Long term customers will likely expect better service than new customers, but it is imperative to provide good customer service to new customers also. Retaining customers will be important once the pandemic is over since sales will likely drop precipitously, not necessarily to pre-pandemic levels, however. Flexibility and responsiveness are likely the two most important factors that PPE companies will have to consider while there is uncertainty in the PPE market.

The PPE industry has faced some ethical issues during the pandemic. To fulfill orders, the companies were shipping masks where COVID-19 was most prevalent, but that was outside the US and created a backlash. When the companies began shipping only within North America, the public was pacified, but at what cost? It has been shown that there were more masks available to the US, but companies were unsure how to distribute them effectively. 3M, specifically, ramped up production to 24 hours a day and are producing as much as they can and began direct distribution to hospitals and medical facilities (instead of distributors), but there is still the public opinion that there is a shortage of supplies. 3M had a pandemic plan in place and reacted quickly, but it is hard to know if there was more that could have been done with any new technology.

CONCLUSIONS AND CALL FOR FURTHER RESEARCH

We have come to several tentative conclusions based on preliminary research results here. First, centralized coordination of the pandemic response was absent, so PPE supply chains responded as commercial supply chains, acting on the information that was available. Second, PPE producers and distributors were overwhelmed by demand in the early stages of the pandemic, but responded in a way that was definite by the market and government requirements. Third, the PPE

supply chain was prepared for this pandemic to about the same degree as other commercial supply chains, which is to say not at all.

As we stated from the outset, these results and conclusions are preliminary and tentative. They leave open a broad range of questions for future research. These include: Does a pandemic require central coordination in the US or can states, given sufficient notice, prepare and respond individually? Should the US and other countries maintain a strategic stock of PPE and other supplies in anticipation of another pandemic? If so, how should that stock be handled to deal with inventory aging, warehouse location, network design, transportation, and priority setting?

More broadly, what can governments and private firms at all levels do to respond more rapidly and effectively to pandemics and other disasters? This is hardly a new question. Whole journalson humanitarian supply chains examine questions related to this. And finally, what lessons can PPE and other supply chains take from the events of 2020-21?

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