Research Opportunities in Preparing Supply Chains of Essential Goods for Future Pandemics

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Abstract: The COVID-19 pandemic severely tested the resilience and robustness of supply chains for medically critical items and various common household goods. Severe and prolonged shortages of personal protective equipment (PPE) and ventilators in the United States have revealed vulnerabilities in the supply chains of such essential products in a time of need. Consequently, corporations have felt public pressure to rethink their supply chains. We begin this paper by examining the underlying causes of the prolonged shortages of critical products in the US as well as government's and some companies' initial response. Drawing from the lessons learned from the COVID pandemic, we propose a research agenda and opportunities to develop responsive supply chains to fight future pandemics. These opportunities revolve around measures that are intended to improve the supply chain responsiveness of essential products to combat future pandemics and other major public health emergencies.

Keywords: Pandemic, global supply chains, resilience, industry commons, preparedness

1. Introduction

COVID-19 is the first genuinely global scale pandemic since the 1918 flu pandemic, which infected one-third of the world's population and claimed 50 million deaths worldwide (Johnson and Mueller, 2002). Although the rapid spread of COVID-19 disease (caused by the SARS-CoV-2 virus) has caught governments and companies by surprise, predictions of the spread of such a virus (i.e., coronavirus) have been rife since SARS hit China in November 2002. From a review of the literature, Cheng et al. (2007) warned about the "*the reemergence of SARS and other novel viruses from animals or laboratories*," and we may see such a pandemic again in the not-too-distant future. Apart from creating an international public health crisis, the COVID-19 pandemic disrupted the supply of *essential goods*, including medically critical goods and common household goods. Severe scarcity of Personal Protective Equipment (PPE) and ventilators in the US has revealed vulnerabilities in the supply chains for critical products.

To guide research on preparing such supply chains for future pandemics, we first examine the underlying causes of the prolonged shortages of critical products in the US, and the government's and companies' response. Drawing from the lessons learned from COVID-19, we propose a research agenda to ensure supply chains for essential products can quickly respond to future pandemics and other major public health emergencies. The agenda comprises operations management (OM) research opportunities to continue developing responsive supply chains to fight future pandemics.

Our paper is positioned in the supply chain risk management literature motivated by COVID-19, particularly in the recent literature outlining research directions as well as the literature with more practical bent. As Choi et al. (2020) point out, COVID-19 is a wake-up call for supply chain management, and therefore researchers are trying to infer opportunities and shape future research. Craighead et al. (2020) use ten different theories – resource dependence theory, institutional theory, game theory, and others – to draw out research questions, offering ways for simultaneous transformation and resilience, i.e. *transilience*. Besides resilience and robustness discussed in the literature, Ivanov and Dolgui (2020) bring up an additional notion of *viability* – the system's ability to just survive – of a supply chain network in the face of disruptions. Queiroz et al. (2020) use a structured review of papers in the OM and the operational research literature on the impact of epidemics or pandemics on supply chains to outline a research agenda. Their agenda is based on adaptation to reallocate supply; preparedness; ripple effects in supply chains; recovery; sustainability (including humanitarian relief); and adopting digital means. Sarkis et al. (2020) see 'a window of opportunity' for sustainability as a result of COVID. There have also been calls in 2020 inviting articles for special issues on supply chain lessons from COVID, for instance *Decision Sciences*, *International Journal of Production Research*, *Journal of Operations Management*, *Journal of Supply Chain Management*, and *Productions and Operations Management,* among others. On the practical side, there are gaps between industry practice and the resilience literature (Sodhi et al., 2012), but these gaps can be closed (van Hoek, 2020). Govindan et al. (2020) develop a decision support system to mitigate the effects of the disruption to healthcare supply chains during a pandemic by categorizing individuals in communities by vulnerability. Like us, Paul and Chowdhury (2020) are motivated by the twin problems of unexpectedly high demand and the constrained supply of essential goods; they offer a nonlinear programming model to guide the manufacturer develop an optimal recovery plan. Ivanov and Das (2020) develop simulation models to examine the implications of various pandemic supply risk mitigation measures and potential recovery paths.

We seek to contribute to this literature by outlining research opportunities on resilience of the public infrastructure against public health emergencies like COVID-19. These research opportunities are particularly centered on the notion of "capability," and we hope this paper will stimulate further research in supply chain responsiveness in disruptions. We also contribute with research opportunities to do with supply chain design and restructuring for mitigating the impact of extreme disruptions, including public health emergencies. On the practical side, our focus is on *public policy* using the United States context as an example.

The rest of the paper is as follows: In Section 2, we highlight well-documented shortages of household paper products (toilet paper, paper towels, disinfectant wipes) and those of critical medical products including PPE (masks, respirators, shields, surgical gowns) and ventilators. In Section 3, we identify the underlying causes of the prolonged shortages based on our analysis of the supply chain operations associated with different products and examine the US government's makeshift response in Section 4. Section 5 presents new OM research opportunities around ideas on how to develop the responsive supply chains, whether those for disaster management or for household goods in public health emergencies before the conclusion in Section 6.

2. Motivation: COVID-19-Related Shortages of Essential Goods

By the end of September 2020, there were already 33 million confirmed cases of COVID-19 infection, which had resulted in a million deaths reported worldwide as of (Source: worldometer). These numbers are likely underestimates due to the low levels of testing in many countries. The US had over 7.25 million confirmed cases, with India and Brazil following close behind with over 5.9 million and 4.7 million confirmed cases, respectively.

Not only has the COVID-19 virus created a worldwide public health crisis, but its spread has also plunged the world into a global economic crisis. The International Monetary Fund (IMF) reported that the global economy would shrink by 4.9% in 2020 rather than grow by 3.5% as predicted before the pandemic. The drop would be the biggest since the Great Depression of the 1930s (Jones et al., 2020). Many countries have reduced interest rates and have used reserves to subsidize industry or wages. However, with interest rates falling below zero in several countries, additional options to stimulate growth are limited. Changes in consumption patterns combined with generally weaker demand have resulted in a sea change in many industrial sectors. Tech industry giants have been among the largest beneficiaries as they watch their stock prices soar. As of this writing, the eventual impact remains uncertain.

At a more tangible level, demand for essential goods – toilet paper as a common household item, hand sanitizer, PPE (face masks, N95 masks, medical gowns, etc.) and ventilators as medically critical items –surged as numbers of confirmed cases grew. The surge resulted in shortages as supply chains struggled to increase production to the levels necessary to meet these rapid demand spikes. In some countries, the backlog to restock PPE inventory ranged from 6 to 12 months (Frost and Sullivan 2020). Demand increases also caused prices to skyrocket, with the World Health Organization (WHO) reporting that surgical masks' prices increased six-fold, N95 respirator prices tripled, and gown prices doubled. Urgency, coupled with longer delivery times and prices, led to market manipulation and outright fraud.

Shortages of essential products stoked public fear and anxiety during the crisis, especially in the United States. According to the media database provided by Muckrack.com (**Figure 1**), the number of articles issue of shortages of toilet paper and face masks peaked in March, while news coverage over PPE (face masks, N95 masks, medical gowns, etc.) and ventilators peaked in April. However, the media discussion of PPE shortages in the US continued even in late August (Bender and Ballhaus, 2020).

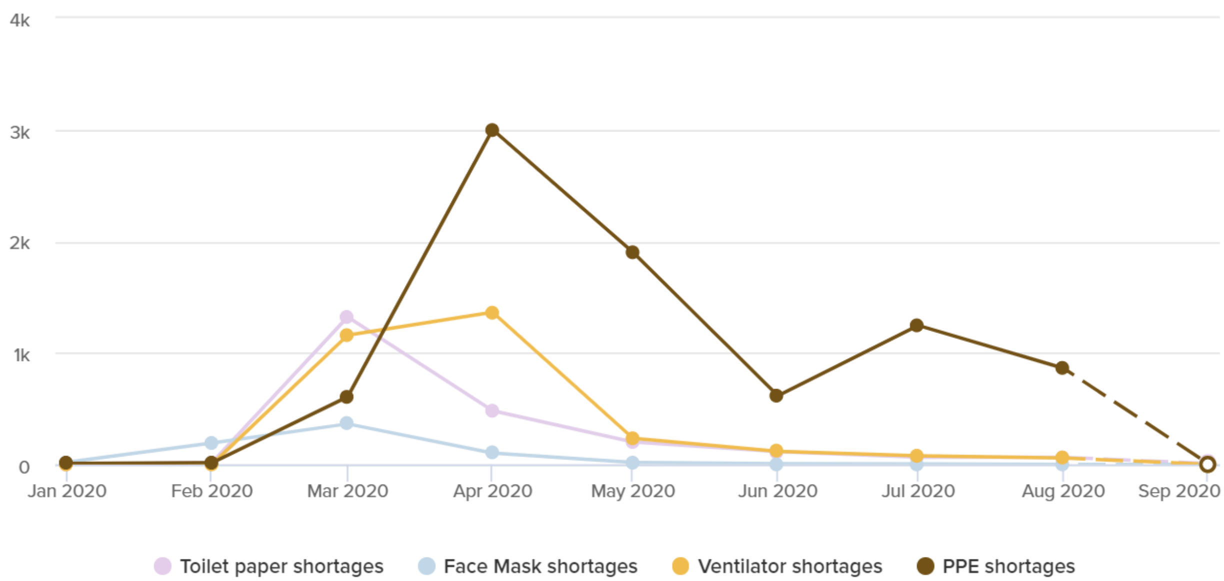

Figure 1. The number of news articles published about shortages. Source: Muckrack.com

Examples of shortages the public experienced in 2020 in the US were:

1. **Household paper products and disinfectant wipes.** In March 2020, many US cities issued stay-at-home orders. Consequently, demand for household products such as toilet paper, paper towels, and disinfectant wipes surged, partly from fear of shortages and partly from increased consumption at home. Meanwhile, the market for commercial size toilet paper and paper towels plummeted. Because of this sudden demand shift, over 60% of US grocery stores experienced out of stock for toilet paper between mid-March and mid-April (Geller and Baertlein, 2020). News of shortages snowballed into panic buying and hoarding, making the situation worse. Household paper products such as toilet paper, paper towels, and disinfectant wipes were still out of stock at stores even in early August. Also, household goods manufacturer Clorox anticipated that the shortage of its wipes would continue into

2021 (Terlep and Gasparro, 2020).

2. **Face masks.** The US Center for Disease Control (CDC) recommended facial covering and social distancing in early April (Dwyer and Aubrey, 2020). As different cities issued mandates requiring face coverings to slow the spread of COVID-19, the demand for face masks (mainly surgical masks) jumped, leading to severe shortages.

3. **PPE.** As Covid-19 associated hospitalizations surged in April and then in July, demand for the PPE that protects healthcare providers surged. As worldwide demand grew, the current supply of PPE was grossly insufficient. Prolonged shortages of personal protective equipment (PPE), especially N95 masks, led to over 300 deaths and 60,000 infections among US health care workers by the end of May 2020 (Stone and Feibel, 2020).

4. **Ventilators.** Considering the number of ventilators in stockpile or current use, scientists estimated in April 2020 that an additional 45,000 invasive ventilators and 77,000 non-invasive ventilators were required to provide care for all COVID-19 patients in need (Wells et al. 2020). At the same time, it was discovered that over 2,000 ventilators in the US stockpile have either past their expiration date or otherwise unusable (Sangler, 2020).

As the world's largest economy, representing 24% of global economic output, the prolonged shortages of PPE shocked the public, especially when the United States' health care spending accounted for 17.8% of GDP in 2019. In March 2020, the image of three Mt. Sinai Hospital nurses outfitted in trash bags due to lack of available PPE went viral on social media. By the end of August, Cohen (2020) reported that doctors and nurses were still reusing single-use N-95 masks and experiencing shortages of face shields and gloves. The American public was shocked by the prolonged scarcity of PPE despite the colossal health care budget. Companies making these and other goods also face supply constraints at the same time as demand surges (Yu et al. 2020). The state of the Strategic National Stockpile also reflected poor preparation as some states received expired, rotting, or otherwise unusable masks, gloves, ventilators, and other essential equipment from the national stockpile (Chandler, 2020). To a large extent, severe prolonged shortages of Personal Protective Equipment (PPE) and ventilators in the US triggered the need for supply chains of essential products to respond quickly to future pandemics and other major public health emergencies.

3. Underlying Causes for Shortages

Before proposing a research agenda to improve supply chain responsiveness in such extreme situations, let us examine the underlying causes of the previously discussed prolonged shortages.

3.1 Prolonged Shortages of household paper products

When "stay at home" orders began, demand for household paper products (toilet paper, paper towels, disinfectant wipes) increased, while consumption for similar paper products for commercial and office use decreased. Medical experts televised virus containment methods by sanitizing various surfaces. Consumers started liberally using antibacterial wipes on items such as groceries, delivery boxes, and mail.

Thus, consumption shifts driven by the stay-at-home orders and hoarding caused demand to surge. Because shortages were quick and sudden, fear and uncertainty of future availability triggered consumers to purchase and retailers to order even more. The “bullwhip” effect was massive as some retailers increased their order quantity five-fold in one week, and then ten-fold in the following week (Terlep and Gasparro, 2020). Despite manufacturers such as P&G, Georgia-Pacific, and Kimberly-Clark having real-time sales information from Walmart and other retailers, the manufacturers could not meet surging demand for the following reasons.

Just-in-time production systems. With demand increasing tenfold in a matter of weeks, production could not keep up with supply chains continued to operate in a just-in-time fashion. Pioneered by Toyota, the just-in-time operations for producing household paper products have functioned well for decades because consumption sales rates have been stable (e.g., non-seasonal) before the pandemic. In a just-in-time system, there is little finished-goods or raw material inventory in the supply chain. Even retail stores don’t carry much of these items. Therefore, any unanticipated disruption to supply or a surge in demand can result in a stockout.

During the pandemic, there were significant disruptions to replenishing raw materials for many household items sourced from China. In January, after the COVID-19 outbreak in China, all factories were slowed or shut down until late March. As factories resumed operations, the supply of products for buyers was limited. For example, supplies of quaternary ammonium compounds (the requisite ingredients for making antimicrobial disinfectant chemicals used in disinfectant wipes and sprays) and the supply of plastic packages (e.g., wipe canisters, hand sanitizer pumps, spray bottles) were particularly hit.

In addition to supply disruptions, before the pandemic, most paper product manufacturers usually operated at full capacity and could not increase production without incurring significant changes. The capacity was designed to very closely match the historically stable demand. Without spare capacity and pre-existing inventory, the just-in-time system could not respond and increase production to meet demand surges.

Inflexible manufacturing and distribution systems. Because the manufacturing lines for producing paper products are operating according to a *batch process.* These lines produce high volumes and yet inflexible and, hence, unresponsive. It is difficult to switch these lines from making commercial paper products to household paper products. The manufacturing lines produce 120 large rolls per pack for commercial paper products compared to the lines for household products, making 6, 12, or 24 rolls per pack with much smaller rolls. The logistics and distribution processes are also different due to differences in palletization requirements and packaging. Inflexibility means it takes a long time to switch manufacturing lines from producing commercial to household products. Similarly, systems for producing household toilet paper and paper towels are not interchangeable. Toilet paper uses pulp treated with specific chemicals to ensure toilet paper dissolves in sewage systems quickly. Additionally, each automated system makes a particular product with a particular length, size, package size, etc.

It would require a significant overhaul of hardware and software to convert a production line from one type of household paper product to a different kind (Terlep and Gasparro, 2020). A more straightforward way to increase capacity is to reduce product variety. Georgia-Pacific, the Sparkle paper towels manufacturer, reduced product varieties – two-ply, three-ply, the number of sheets per roll, the number of rolls per package – and increased capacity by 25%. However, the increase was still inadequate to fulfill all retail order demand surges.

3.2 Prolonged Shortages of PPE and Ventilators

Consider these root causes for the prolonged shortages of PPE and ventilators:

Inconsistent policies and poor management of the National Stockpile.[1] Ideally, there should be a long-term commitment to maintaining a stockpile of critical items in case of a public health emergency at both the state and national levels. California built a considerable stockpile, including ventilators, in 2005 under Governor Schwarzenneger. But the reserve had to be dismantled in 2011 by Governor Jerry Brown as a cost-cutting measure to reduce the state's budget deficit.

Also, the US Department of Health and Human Services (HHS.gov) maintains the Strategic National Stockpile. Despite its sizeable annual budget for the Stockpile -- $603 million for 2019 – HHS has found it challenging to manage a stockpile of medical equipment over two-three decades. Managing the Stockpile requires procurement, inventory rotation, audits, and inspection to ensure all items are in good working condition. As mentioned before, over 2,000 ventilators and a significant proportion of PPE in the US stockpile were unusable at the start of the pandemic, suggesting that the HHS has not managed the National Stockpile adequately.

Poor PPE supply chain risk management. When firms began outsourcing their manufacturing operations, and when the government started sourcing from overseas suppliers, they should have established visibility into supplier operations and assessed potential supply risks. However, when the federal government agencies, states, local governments, and hospitals rushed to compete for supplies from the same set of foreign manufacturers in April, the absence of risk management practices created the world's largest gray market (Dai and Tang, 2020). Unethical overseas

[1] The Strategic National Stockpile is a massive inventory-based approach for demand surges caused by public health emergencies. Suppose a community experienced a large-scale public health incident in which the disease or agent is unknown. In that case, the intent is to send a broad range of pharmaceuticals and medical supplies from strategically located warehouses throughout the US in 50-ton containers to any state within 12 hours of the federal deployment decision.

suppliers cropped up and made a fortune, often without delivering quality products, if delivering at all. For example, the National Institute for Occupational Safety and Health found that 60% of 67 different types of N95 masks imported from China failed to provide adequate protection, offering as little as 24% filtration instead of the required 95%. Over 1,300 Chinese medical suppliers, including 217 N95 mask manufacturers, used false addresses and non-working numbers in their registrations with the Food and Drug Administration (Hufford et al. 2020).

Many private sector firms do not even know their distant suppliers (Tang, 2020). Based on a 2018 survey conducted by Deloitte,[2] 65% of more than 500 procurement leaders from 39 countries had limited or no visibility beyond tier-one suppliers. Further, private sector firms do not provide visibility to the FDA. Current FDA regulations require PPE manufacturers such as 3M and Honeywell to report only their factories' locations, rather than essential supply chain information such as their domestic and overseas production capacity (Dai and Tang, 2020). Without supply chain visibility, healthcare providers cannot manage their PPE procurement risk. Without knowing their suppliers' true identity, providers cannot scrutinize them to prevent adulteration and other quality issues, which further delay the response to a pandemic.

Inadequate product design, development, and manufacturing capabilities. Since the 1980s, many US corporations offshored and outsourced their manufacturing operations to China in particular. With improvements in productivity, quality, and cost-efficiency, China has become the world's factory: China is the largest producer of LCD TVs, printed circuit boards, rare earth minerals, API (active pharmaceutical ingredients), and PPE, etc.

On the flip side, decades of offshoring and outsourcing have hollowed out the US manufacturing sector. Between 1980 to 2017, roughly 7.5 million jobs were lost in the manufacturing industry (Hernandez 2018). Despite the increase from 2011-2019 (**Figure 2**), the US Bureau of Labor Statistics predicts negative compounded annual job growth in the manufacturing sector to be -

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2 Deloitte (2020). Two in three procurement leaders have limited or no visibility beyond tier one of their supply chain. Accessed https://www2.deloitte.com/uk/en/pages/press-releases/articles/procurement-leaders-have-limited-o-no-visibility.html on 7 Oct. 2020. In the same vein, Choi et al. (2020) reported that, based on a survey by Reslinic in late January and early February after the Covid-19 outbreak in China, 70% of the 300 respondents said they were trying to identify which of their suppliers were in locked-down parts of the country.

0.4% per year from 2019-2029. By contrast, the Bureau expects a yearly increase in the number of jobs to be positive in educational services (+1.2%), healthcare and social assistance (+1.4%), professional and business services (+0.7%), and leisure and hospitality (+0.7%). These statistics suggest that the Bureau expects that, in the long term, companies will continue outsourcing manufacturing capabilities. As the Chinese companies seek further opportunities in the manufacturing value chain (Sodhi and Tang, 2013), product design and development would also go the same way as manufacturing capabilities.

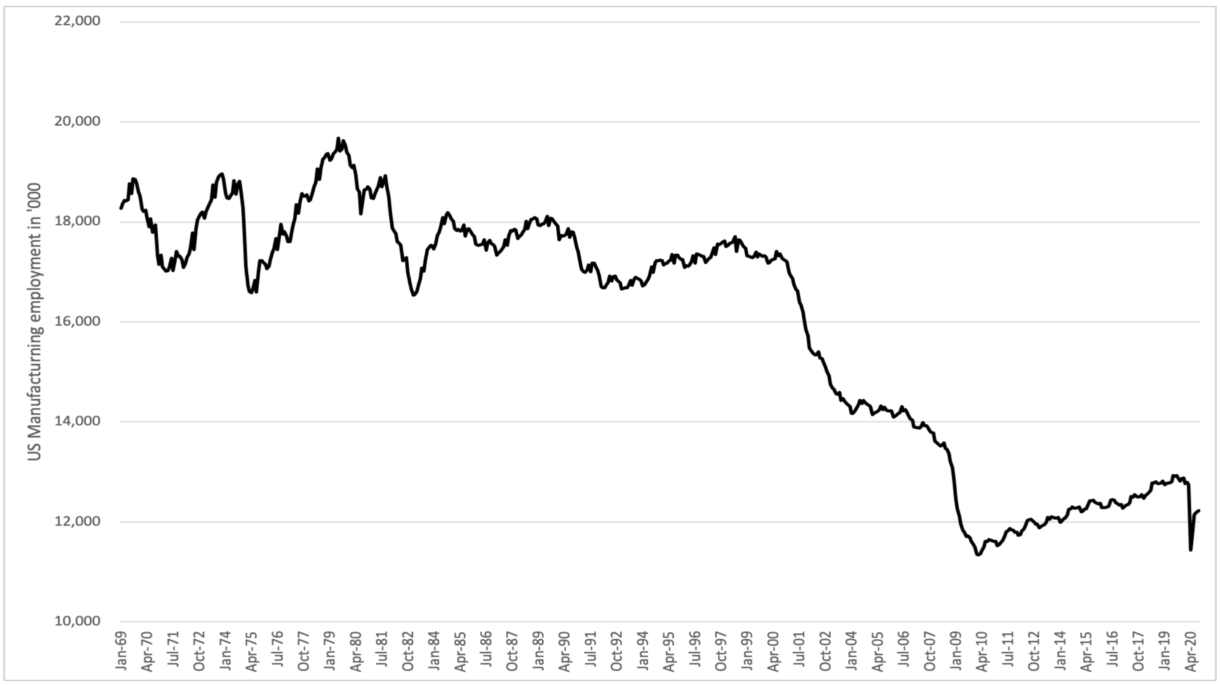

Figure 2. Monthly US manufacturing employment from January 1969 to April 2020. Source: Archival Federal Reserve Economic Data and US Bureau of Labor Statistics

4. Makeshift Responses Amid the COVID-19 Pandemic

During the COVID-19 Pandemic, many US firms could not get PPE orders filled within a reasonable time window because China had first to secure its own PPE supply after manufacturing operations resumed. Even when Chinese factories could produce US orders, it was a big challenge to ship products to the United States. All cross-border logistics have been either suspended or disrupted due to border and port closures, flights' shutdown, and quarantine requirements for ocean freight personnel. When supplies from China were uncertain, there were calls for more production within the US. Despite efforts by the government and leading manufacturers, the US simply did not have the right equipment, the requisite materials, and the know-how to overcome the shortages. Consider three examples:

1. **The rapid development of new ventilators.** In late March, the US government expected that there would be a severe shortage of both invasive and non-invasive ventilators. In response, President Trump invoked the *Defense Production Act* to ask US manufacturers to produce ventilators quickly by creating consortia. For example, automaker G.M. and Ventec, a medical equipment maker, formed a partnership to build ventilators at a GM plant in Kokomo, Indiana (Gardner and Garsten, 2020).[3] The consortium shipped 600 ventilators by mid-April and was on schedule to produce 30,000 ventilators through the end of August (Nickelsburg, 2020). However, the mechanical ventilators made were basic in functionality because of the rush project and could not fully support a patient's breathing (O'Kane, 2020).

2. **Rapid production of face masks.** Faced with severe shortages of face masks, the government asked Brooks Brothers and Hanes to retrofit their US factories to produce masks and gowns for medical professionals (Tang, 2020). Although face masks are easy to manufacture, it is necessary to produce filters by using a conventional technology called *melt blowing* to block germs or minute particles.[4] Unfortunately, the US has limited capacity to make melt-blown fabric because it has been viewed as a commodity and cannot quickly expand the production of melt-blown material in the US. Additionally, the equipment for making melt-blown fabric is expensive at $4 million per machine and in short supply. Due to worldwide shortages of surgical masks and N95 masks, China suspended its exports of masks and melt-blown fabric between late February and late March. For these reasons, Brooks Brothers and Hanes could manufacture only basic masks, not the surgical or N95 masks that

[3] Simultaneously, Michigan-based Creative Foam Corp. and Minneapolis-based Twin City Die Castings, both auto industry suppliers, repurposed their capacity to provide parts at high volume for the GM-Ventec endeavor. At first, the consortium planned to produce 30,000 of Ventec's premiere product with 700+ components for which it had identified most of the suppliers. The government balked at the $1 billion price tag. Hence, GM and Ventec switched to a more straightforward design with half the cost, but only the single ventilator function without oxygen-related features.

[4] A proper surgical mask comprises three layers: an outer hydrophobic non-woven layer, a middle melt-blown layer, and an inner soft, absorbent non-woven layer. The outer layer repels water, blood, and body fluids; the middle melt-blown layer is designed as the "filter" to stop germs from entering or exiting the mask; and the inner layer absorbs water, sweat, and spit.

can effectively protect healthcare workers.

3. **Increased production of respirators**. Lack of capacity has forced companies to form partnerships to meet demand increases. Before the pandemic, 3M was producing 1.1 billion of respirators annually. However, the company only made 15% of those for the healthcare industry (Frost & Sullivan, 2020). To increase production 3M partnered with Ford Motor Company in March 2020 to manufacture powered air-purifying respirators. In April 2020, 3M signed an agreement with Cummins to manufacture particulate filters used in respirators. As of June 2020, 3M was producing over 1 million N95 respirators per day for healthcare workers.[5] The setup time for companies to establish partnerships was a large contributor to the US's slow response to the virus. To prepare for future emergencies, the US Department of Defense has signed a $126 million contract with 3M to produce an additional 26 million N95 masks starting in October 2020 (Department of Defense, 2020).

These makeshift responses were, therefore, either ineffective or unsustainable. We need ways to improve supply chain responsiveness to meet sudden demand surges during future pandemics, including supply-chain-related measures for governments and individual companies to take. Developing these ways requires an ambitious research agenda because not only can we expect pandemics in the future after COVID-19 is over, but future pandemics will likely occur more frequently as predicted by many scientists (Schmidt and Undark, 2020). Multiple research methodologies will be needed with results feeding into a complete research stream (Sodhi and Tang, 2014). We discuss some approaches, categorized by research opportunities centered on US government preparedness and response, and those centered on the private sector.

5. Research Opportunities

We now present some future research ideas for OM researchers to explore. Supply chain risk management provides a theoretical framework comprising four steps: (1) risk identification; (2) risk assessment; (3) risk mitigation; and (4) response to risk incidents (Sodhi and Tang, 2012). For the pandemic – COVID-19 and future pandemics – we have *identified* various risks by way

[5] An N95 mask is a respiratory protective device designed to achieve a close facial fit and efficient airborne particles' filtration. Unlike the surgical mask, the N95 respirator's edges form a "seal" around the nose and mouth.

of disruption to the supply chains of certain products and processes. Risk *assessment* could be done using simulation (Ivanov 2020) or otherwise to predict impact on an industry, say auto (Haren and Simchi-Levi, 2020), so that *mitigation* steps can be taken. Our focus here is response and preparedness for the next pandemic.

5.1. Applicability of traditional supply chain resilience for pandemics

Recall from Section 3.1 that just-in-time systems and inflexible manufacturing systems caused shortages of household paper products. Traditional approaches include using extra inventory and capacity, diversifying suppliers, and increasing system flexibility to mitigate the risk of shortages of household paper products (Chopra and Sodhi, 2004). The OM literature has examined these issues at length, and Snyder et al. (2016) provide a comprehensive review. Therefore, companies and the government can use traditional OM models to manage household paper-product supply chains for fighting future pandemics. To overcome the shortcomings of current practices, companies can consider the following proven strategies as discussed in Tang (2006).

First, the just-in-time system (or the pull system) uses the lean concept and is cost-efficient when demand is stable, and supply is reliable. However, during a pandemic, demand can surge and become volatile, while supply can simultaneously become unreliable. Redundancy in extra inventory or excess capacity can be the first line-of-defense for firms to respond to disruptions and functions as a buffer to prolong essential product shortages as more permanent solutions are constructed. Further, the transportability of such excess inventory and excess capacity is an additional consideration. For example, if excess PPE inventory exists at the state level without reliable delivery mechanisms, smaller more report hospitals and other medical workers may go longer without essential products. Therefore, it may be necessary that hospitals and public institutions maintain private supplies in case of emergency.

Multi-sourcing is another form of redundancy. A firm can drastically reduce its supply risks by diversifying its supply sourcing across three (at most four) suppliers located in different geographical regions (Tang and Tomlin, 2008). This reduces the supply risks associated with the sourcing various raw materials and packaging materials from a single supplier as well as idiosyncratic geopolitical risks. For instance, during Chinese factory closures in February, a focal firm could have obtained supplies from other suppliers in Vietnam or Malaysia and resumed supplies from China once the factories resumed operations. Therefore, having a small number of suppliers in different geographical regions can diversify and drastically reduce supply risks. Indeed, due to the concern over the ongoing trade war between the United States and China, many firms have adopted the "China Plus One" strategy by sourcing from other countries (such as Vietnam) in addition to China (Reiko, 2019).

Second, having a flexible manufacturing process can alleviate shortages of household paper products. By using advanced technology, manufacturers can develop flexible manufacturing systems to quickly shift production of commercial toilet paper to household toilet paper and paper towels to toilet paper. To segment the consumer market, firms have introduced different types of products of varying quality (e.g., number of plies, grams per square meter, etc.) and multiple varieties (scented, quilted, printed, number of rolls per pack), resulting in a considerable number of SKUs. Flexible manufacturing systems enable firms to produce various products without incurring time-consuming and costly changeover operations. More importantly because flexible manufacturing systems allow firms to modify production across SKUs without incurring long changeover time. Also, product variety can be reduced in order to increase the effective production capacity in times of crisis. We argue that paper product manufacturing firms should make their manufacturing systems more flexible (Tang, 2006). .

Finally, a manufacturer can combine the above two approaches by taking a two-pronged approach as follows: Establish sourcing or capacity supply lines. with both a cost-effective plant or supplier with long lead times (which is the present-day capacity) as well as with a time-efficient flexible plant or supplier (Chopra and Sodhi, 2014). The flexible plant or supplier would handle short-term fluctuations for different products, thus avoiding missed sales. In case of a disruption at the cost-effective plant, the flexible unit can serve as a stopgap solution until the cost-effective plant resumes operations.

Although the above approaches are well understood in the supply chain risk literature, researchers should examine the effectiveness of these traditional approaches for responding to supply and demand disruptions of household paper products caused by future pandemics especially when the demand is based on the uncertain exponential spread of the disease across space and time which differs from other types of disruptions such as those caused by fire or flood (Sodhi and Tang, 2014).

5.2. Understanding national stockpiles against public health emergencies

Based on the root causes of the prolonged shortages of medically critical goods discussed in Section 3.2, to understand the scale and effort required at the national level, researchers need to consider case studies and establish empirical support for the following: Proper maintenance of the National Stockpile of PPE and medical equipment is necessary to respond quickly to pandemics and other disasters. The National Stockpile had 12 million N95 masks and 30 million surgical masks in storage (even though many of them turned out to be unusable when needed) (Cohen, 2020). No matter how much inventory is in storage, it is necessary to audit, inspect, and rotate the stock to ensure usability during a future emergency. Although notions of inventory as well as disaster management are established in the literature, unlike traditional inventory management, the scale and rarity of pandemics will require researchers need to investigate *the logistics of maintaining stockpiles and what it takes to manage them*   using case studies and analytical models. For instance, how many units to store? How often should one inspect the units in storage?   How often should on rotate the inventory? How quickly and to what distance can inventory be deployed?

5.3 Government incentives and reshoring: What, how, and how much?

Not having manufacturing operations within a country can affect a government's ability to orchestrate a response to a massive public health emergency. After experiencing the global supply chain "frictions" during the COVID-19 pandemic, there is public support for reshoring the manufacturing operations back to the US (Loh and Tang, 2020b). US presidential candidate and former Vice-President Joseph Biden proposed a plan (https://joebiden.com/supplychains/) in July 2020 to "implement fundamental reforms that shift production of a range of critical products back to US soil, ... protecting US supply chains against national security threats." Some state governments in the US like Texas and South Carolina are encouraging firms to bring back at least some of their offshore manufacturing capacity (Dai and Tang, 2020b).

Still, for a country like the US with most manufacturing being offshored, it would still be a knee-jerk reaction to try reshoring all manufacturing operations. Researchers must investigate *how to determine which products (or which part of the supply chain) companies should bring back in-country and how much capacity to build up*. Boston Consulting Group (BCG) argues that one should consider the demand volatility and response time in addition to direct cost (Sirkin et al. 2011). However, a more in-depth study is needed.

Companies may not find domestic supply chains to be financially viable when facing sharp demand swings within the country. Multinational companies seek economies of scale by concentrating manufacturing capacity of different products in different locations worldwide in order to pool global demand and dampen such swings. However, if domestic capacity in the US was more flexible, it could handle normal fluctuations for multiple products while continuing to primarily source from foreign suppliers and manufacturers. . A company can then cost-effectively meet demand from its global capacity during normal times and still maintain the ability to meet some demand through flexible domestic capacity in response to public health emergencies. Thus, researchers can study the reshoring decision from this 'hybrid' perspective.

Researchers can also look at components and raw materials. When the components (or raw materials) are produced in offshore locations, Chen and Hu (2017) show that reshoring manufacturing operations for finished goods back to the US is not sufficient, especially when the necessary components' expedited shipping cost is high. Their work is relevant to the reshoring decision for PPE supply chains. When deciding whether to reshore the PPE manufacturing operations back to the US, it is necessary to consider product components as well. For example, when evaluating reshoring the surgical or N95 mask manufacturing operations, the company must also consider the ability to reshore production of melt-blown materials in the US. Therefore, researchers need to consider *different supply chain configurations that involve reshoring the manufacturing operations of various aspects of the supply chains of critical medical products like PPE*.

There are further considerations of government subsidies and other incentives for manufacturers to create or reshore capacity. The demand for PPE and ventilators can vary dramatically over time. For example, the annual need for masks was 3.5 billion during the COVID-19 pandemic

(Cohen, 2020), but only a few million otherwise. While there was a panic to produce ventilators in March 2020 quickly, there was an oversupply of ventilators as of the end of August when less invasive treatments[6] became more effective (Siddiqui, 2020). In response to the ventilator oversupply, the Department of Health and Human Services (HHS) abruptly canceled the remainder of their contract with manufacturer Philips in August (Feure, 2020). Significant cash expenditure is needed to increase production, so contract cancelation can create significant financial hardships, especially for smaller manufacturers. Such potential hardship can justify manufacturers asking for government incentives.

When evaluating different supply chain configurations that involve reshoring, the evaluation criteria include (a) relevant cost, (b) responsiveness toward demand changes (especially during a pandemic), and (c) financial sustainability. Financial sustainability if important for PPE and ventilator supply chains because the demand is low in standard time and high (or very high) during a pandemic. Reshoring the PPE supply chain back to the US may not be financially sustainable if the company cannot obtain economies of scale in the manufacturing facilities in normal times. If the reshored operations' capacity is too high, the company will have too much idle capacity most of the time. The government may need to provide companies subsidies and other economic incentives to encourage reshoring with either more expensive flexible capacity or by having excess capacity that remains idle most of the time. Manufacturers ask for incentives even if they already have a business case, so researchers could examine *the interplay between government subsidies and firms' reshoring*. For instance, which portion of the supply chain operations should the government provide subsidies and incentives to entice reshoring?

5.4 Bolstering inventory with backup capacity for responding to public health emergencies

During the first eight months of the pandemic, the US annual demand for protective masks ins 3.5 billion, or roughly 100 times larger than the amount in the National Stockpile (Cohen, 2020).

[6] Recent research shows that ventilators create other long-term problems (e.g., blood clots) for patients and may not improve survival odds. Instead, many doctors now prescribe less invasive treatments: flipping patients on their sides or stomachs to aid in breathing or providing continuous oxygen flow through a constant positive airway pressure (CPAP) machine.

However, it is not realistic to store billions of N95 masks, because masks will expire after 3 to 5 years. When the timing and scale of a pandemic are highly uncertain, it is challenging to determine appropriate stockpile inventory levels. Having too much is costly, and having too little can be very risky. Therefore, inventory must be bolstered by backup capacity that comes into production (or is diverted from other goods) when demand is expected to exceed inventory. Essentially, such capacity must be available when needed, either by diverting from current manufacturing or because it can be put together quickly. Note that backup capacity would still require inventory or reliable access to components and raw materials. For researchers, given the long tail of the probability distribution of the number of people affected in any year by pandemics (or other public health emergencies) in the country, the question is *how much inventory and how much backup capacity to have for any given year*.

5.5 Understanding the role of standby capability for responding to public health emergencies

It is attractive to improve the national capability to design, develop, and produce critical products domestically not just for having responsive capacity in case of a pandemic, but also for creating high value jobs. Manufacturing capability requires an ecosystem of designers, university and industry R&D centers, engineering firms, manufacturers to convert capability to production capacity for critical products. Shared resources of such a capability have been termed an "industrial commons" (Pisano and Shih, 2009). Any government will need to engage the private sector and university research centers with incentives, tax credits, and grants to establish organizations and training programs to expand the national ecosystem's capabilities.

In recent decades many US students have shied away from STEM (science, technology, engineering, and mathematics), partly because outsourcing and offshoring decreased the need for domestic manufacturing. The US had 568,000 STEM graduates in 2016 compared to over 4.7 million from China in the same year (Loh and Tang, 2020a). Unless there is a long-term commitment from the government to build capability including STEM graduates, it will be challenging for the US to re-establish STEM capabilities.

Developing manufacturing capabilities takes commitment and a coordinated long-term plan that is a research opportunity by way of *studying industrial policy*. The US (or any other) government needs to take a multi-pronged approach to develop responsive supply chains to fight future pandemics. Shortages of PPE and ventilators should serve as catalysts for the US government to develop an industrial system to characterize the products and requisite capabilities required to deploy resources in times of need.

During the decline of the auto industry in the early 1980s, former US secretary of Labor, Robert Reich, argued that the US should develop an industrial policy that focuses on specific business segments to regain its full international competitiveness (Reich, 1982). Amid the COVID-19 Pandemic, US Senator from Florida, Marco Rubio, called for a sensible industrial policy that supports job creation over short-term corporate gain (Rubio, 2020). By leveraging prolonged PPE shortages as triggers, Rubio argued that a resilient American economy requires investment in workers, equipment, and facilities. Researchers need to understand *the existing or default industrial policy and extant national capabilities*.

In the context of capabilities for PPE production, America Makes (www.americamakes.us) is an Ohio-based non-profit organization that "*supports the transformation of manufacturing in the United States through innovative, coordinated additive manufacturing (AM) and 3D Printing Technology Development and Transition, and Workforce and Educational Development*." Its members include US government departments, private companies, and universities. For example, America Makes seeks to coordinate 3-D printing capability with the FDA and the Veterans Health Administration (VHA) to design a 3-D printed mask approved by the FDA (Sodhi and Tang, 2020). Essentially, by coordinating different people with a variety of expertise, America Makes enables the creation of approved PPE designs for manufacturing with additive manufacturing capability within the country. Also, America Makes has developed a knowledge-sharing platform (Digital Storefront) to share its members' latest information.[7] To a certain extent, America Makes is an *ecosystem* with the standby capability to leverage 3D Printing technology to develop and produce products when needed.

[7] The Storefront is "an online platform where members can access member-exclusive information, project data, and intellectual capital assets, including project deliverables and artifacts along with their association to the Technology Roadmap."

By establishing standby capability, developing domestic supply chains, and keeping the right amount of inventory of PPE and medical equipment, the US government will be better equipped to respond to future pandemics. The US government can also run stress tests and simulations to identify potential gaps in the entire ecosystem as well as in supply chains of essential products. Once these elements are in place, the response to future pandemics is the following: The National Stockpile is the first line-of-defense. Simultaneously, the government begins forecasting demand and checks if the domestic supply chains' backup capacity can handle the predicted increase in demand. If not, the standby capabilities are deployed, converting capability into producing requisite essential products.

5.6 Determining the optimal level of inventory, capacity, and capability for responding to public health emergencies

To respond to volatile demand including demand surges and unreliable overseas supplies, we proposed above that the US government (1) maintain sufficient inventory, (2) develop domestic supply chains backup capacity, and (3) establish standby capability. Researchers need to evaluate *how to compute the levels of inventory, capacity, and national capability needed*.

Assume that the stockpile inventory I is in place to satisfy demand within a short response time T_0 (**Figure 3**). However, the stock I can only support demand for a limited time t as determined by $\int_0^t D(t)\, dt = I$, where $D(t)$ is the demand rate of the product at time t. To estimate the demand during a pandemic, one needs to incorporate different disease spread model such as the S-I-R model.[8] By developing a simulation-based disease spread S-I-R model, Ekici et al. (2014) estimate the spread pattern of a contagious disease across different geographical regions over time.

[8] The SIR (Susceptible, Infected, and Recovered) model is an epidemiological model that computes the theoretical number of people infected with a contagious illness in a closed population over time (Harko et al. 2014).

Recognizing that the total amount of time to distribute products produced by backup capacity is T_1+T_0, the US government will need to start the production at the right time to ensure that units produced by backup capacity will arrive no later than time t.

At the next level of backup, the US government would encourage manufacturers to convert standby capability (e.g., 3D printing capability) into the necessary production capacity to start production. Units produced by converting standby capability would supplement units produced by the backup capacity.

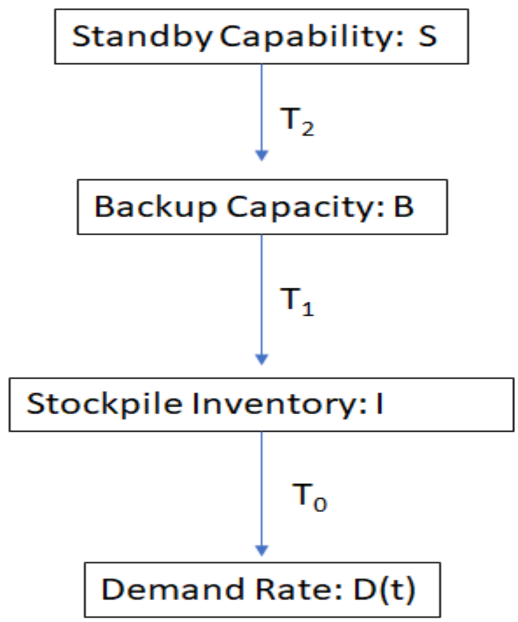

Figure 3. Integrating standby capability, backup capacity, and stockpile inventory.

This integrated three-prong approach resembles the classical multi-echelon inventory system for demand uncertainty. For instance, when IBM needed to improve the service level of repairs using its spare parts inventory stored at different locations (customer engineers, regional warehouses, national warehouses). Cohen et al. (1990) developed and implemented a system called Optimizer for IBM to respond to machine failures at the customer site by maintaining an optimal amount of spare parts inventory at different locations. The underlying modeling is based on that of Cohen and Lee (1988).

Unlike Cohen et al. (1990), we have to make decisions on more than inventory. Our three-stage system involves inventory management, production planning, and capability conversion.

Specifically, in addition to deciding on the amount of stock I for the National Stockpile, we need to decide on the backup *capacity* level *B* and the standby *capability* level *S*.

Further, our objective function is also different. In the multi-echelon inventory literature, the objective is to determine optimal inventory planning policy at each echelon so that the system can satisfy stationary (but uncertain) demand according to a particular service level at a minimal cost. In the case of a pandemic, the demand for PPE and ventilators is non-stationary and uncertain. Our objective is to design our system by choosing *I*, *B*, and *S* by considering the tradeoff between the system's responsiveness to demand surges with the cost of maintaining stockpile inventory, the time required to mobilize backup capacity, and the ability to deploy standby capability. Given the similarities and differences, it would be useful to determine a cost-effective integrated system that effectively adapts to the volatility of pandemic demand swings.

5.7. Allocating goods in high demand with imperfect information

Dai and Tang (2020) reported that the US healthcare system is decentralized and information is fragmented which makes coordination tricky. Currently, there is no centralized data reporting system that allows the federal government to track the number and locations of infections and pandemic-related deaths, PPE consumption, PPE shortages, or production capacity and inventory levels in a timely and accurate manner. Also, there is no incentive for state or local governments to share information truthfully about their PPE inventory because of the fear that the federal government may confiscate the inventory from one state and distribute it to other states.

Without local information, most ordering decisions crucial to public health are made locally with minimal information-sharing at the health provider level. Perhaps this lack of local knowledge has motivated the White House to acknowledge that "*response [to national emergencies] is most successful when it is locally executed, state-managed, and federally supported*." (Bender and Ballhaus, 2020). However, without a coordinated plan, different state local governments rushed to compete for supplies from the same set of foreign manufacturers in April, creating the world's largest gray market for PPE (Dai and Tang, 2020).

When information about PPE supply and demand resides in local state governments, there is an exciting research question about the design mechanism that deserves further examination. *Can* *the federal government control the production and procurement of PPE centrally and develop policy that allocates available units to different local state agencies while inducing competing local state governments to report information truthfully*? This mechanism design problem is reminiscent of a problem examined by Cho and Tang (2014): Facing uncertain demand and limited supply from a manufacturer, multiple competing retailers choose order quantities in anticipation of rationing. When the manufacturer knows the correct demand distribution of each retailer, Cho and Tang (2014) developed an allocation policy so that all competing retailers set order quantities without inflation, even when rationing is imminent. In our context, the federal government does not fully know the supply or demand information. Despite this challenge, *is there an efficient allocation policy that the federal government can implement as a centralized control policy in the absence of verifiable information*?

When centralized control policy is too challenging to contemplate, *is there a mechanism that can entice competing state local governments to cooperate in fighting against the gray market and unethical suppliers*? For instance, each state or local government, and each major hospital should require manufacturers and foreign suppliers to provide verifiable details about PPE production networks and upstream supply chain partners. By posting this information on an information-sharing platform along with customer reviews and ratings, information transparency can force unethical suppliers out of the market, benefitting all state governments.

6. Conclusion

Managing supply chains – whether those of companies manufacturing household goods or the US government managing the National Stockpile with medically critical products –is challenging when demand is volatile and surging, and supply is unreliable as we have seen from COVID-19. We examined the underlying causes of the prolonged shortages of such products in the US and the government's and companies' initial response in the year 2020. To prepare better for future pandemics and other public health emergencies, we presented a research agenda and discussed research opportunities for responsive supply chains or responsive national disaster management systems.

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