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COVID-19 and Beyond: Implications on Supply Chain Network Design*

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ABSTRACT

The unprecedented nature of the COVID-19 pandemic—the global scope, long-lasting impacts, and the simultaneous supply and demand disruptions—calls for a rethink of supply chain network design beyond what was studied in the literature. This study provides managerial insights on the design and operations of supply chain networks for the new normal. Building on the latest theoretical development in supply chain disruption and using an extensive simulation study based on the data of confirmed COVID-19 cases and lockdown measures, we analyze the dynamics of alternative supply chain network strategies under various pandemic-induced disruption scenarios. Our study highlights the principle of robustness, that a supply chain network should be designed to withstand alternative disruption scenarios that could emerge, which can be achieved through strategic design elements. We find that flexibility offers strategic redundancies to effectively combat the sources of uncertainty that trigger the forward and reverse bullwhip effects. In addition, we find that flexibility complemented with the strategies of preparedness and agility can be especially valuable in robust network. In particular, preparedness (securing emergency backup suppliers) is most effective when flexibility is deployed downstream; whereas, agility (proactive stocking policies in response to imminent disruptions) can be most helpful when flexibility is deployed upstream.

Keywords: COVID-19, supply chain disruption, robust network design, flexibility, agility, preparedness

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1. BACKGROUND

The COVID-19 pandemic has profoundly impacted the health and well-being of humanity, having caused over six million deaths as of October of 2022 (World Health Organization). The crisis has severely affected businesses across the world as well due to lockdowns, trading disruptions, production halts, and consumption patterns changes.

The pandemic has also reminded us, especially the supply chain executives, how tightly global economies are interdependent. As soon as the suppliers in Korea took the hit, manufacturers in Europe went down. As soon as Korean manufacturers were back in action, they had to adjust to the weakened global demand. The average capacity utilization of manufacturing industry in Korea was as low as 68.6% in April—the lowest ever since the 2009 financial crisis (Statistics Korea 2020). While the domestic economy is picking up as the Korean government has found success containing the Coronavirus locally, it is unable to feed the supply chain flow under global lockdown. Japan is in a similar situation. Toyota halted operations at five plants in Japan in May and was reported to reduce production at other plants around the globe, amounting to a 50% reduction in production output (Japan Times 2020).

The impacts of the COVID-19 pandemic are different from other types of supply chain disruptions in several dimensions. First, the scope of pandemic disruption has been unprecedented. In other severe disruptions we have encountered in recent years, such as the Tsunami in Japan or wildfires in Australia, the impacts were typically confined to a certain geographical region. However, the impact of COVID-19 is truly global, as over 180 countries have taken measures from partial restrictions to full national lockdowns. Second, the longevity and relentlessness of the pandemic disruptions are much more damaging than other disruptions we have endured since the Second World War. At the time of writing, Europe is fighting a second wave of COVID with lockdowns looming. It is unclear how long it will take for the pandemic to be contained. Third, while the typical disruption affects only the supply side, the pandemic is simultaneously affecting the demand side. The pandemic and lockdowns, as well as the accompanied fear of impending recessions, have caused consumers to increase savings and slash consumption. For example, the household saving ratio in the UK surged by 22 percent in Q2 of 2020 (Office for National Statistics, UK).

Many developed countries, such as U.K., have formulated consistent COVID-19 response strategies composed of several phases: Contain, Delay, Mitigate, Research, and Recover (Department of Health and Social Care 2020). Consistent with this, our research focuses on how to formulate coherent, phased supply chain network strategies to manage and respond to widespread the long-lasting disruptions, and to redesign resilient networks as the crisis subsides. The primary purpose of this study is to provide managerial insights on the design and operations of supply chain networks for the *new normal*. In particular, we aim to address the following two research questions: First, what insights from the conventional wisdom on resilient supply chains from the literature hold (do not hold) under the COVID-19 pandemic, and why? Second, how should firms reshape their supply chain networks and operations strategies to deal with uncertainties through the pandemic and beyond?

To address these questions, we will draw a parallel between the pandemic response strategies and the theories established in the supply chain management literature. Specifically, we aim to build on the latest literature on supply chain disruption and resiliency to discuss strategies that can effectively deal with the COVID-19 pandemic, which has disrupted nearly every component of the global supply chain. Our analysis includes large-scale simulation studies based on the principle of *robustness* to explore viable supply chain strategies to hedge against various types and levels of disruption scenarios that capture various forms of pandemic evolution in the future.

2. RELATED LITERATURE

Research in supply chain disruption has gained considerable attention in the last couple of decades, following disastrous events such as September 11, Hurricane Katrina, and the 2012 Japan earthquake. Our research is particularly related to the ones that analytically examine the design and operations principles of supply chain management in the presence of supply chain disruptions.

First, our research builds on the reliable supply chain network design studies that explore the trade-off between the operations under the normal circumstances and under various disruption scenarios (e.g., Snyder and Daskin 2005, Lim et al. 2010). Mak and Shen (2012) extend the literature by taking into consideration the trade-off between economies of scale and risk diversification. While exploring a robust network configuration, Lim et al. (2013) point out that the impact of misestimating the disruption probability is asymmetric—the consequence of under-estimation can be way more costly than over-estimation—thus suggest to be conservative when estimating the disruption probability.

Whilst the above mainly focuses on the network design perspective, other studies have focused on specific drivers of the supply chain to obtain effective mitigation strategies. These include inventory management (e.g., Dada et al. 2007), flexible supply chain configurations (e.g., Tomlin and Wang 2005, Tomlin 2006, Hopp et al. 2010), and procurement contracts (e.g., Chopra et al. 2007). Among these, Tomlin (2006) and Chopra et al. (2007) show that carrying extra inventory can be effective against the recurring (frequent but short downtime) uncertainties, whereas arranging a reliable source of extra capacity can be effective against the (rare but long downtime) disruption events.

It has been well-studied in the literature that mismatch in supply and demand can cause shockwaves that propagate through the entire supply chain, resulting in a great degree of operational inefficiencies. Similar to the epidemiological models (such as the well-known SEIR model) in pandemic studies, it can be useful to examine uncertainty dynamics through the lens of the classical supply chain theory. For example, the bullwhip effect states that sudden changes (increase or decrease) in demand can trigger amplifying impacts that propagate upstream through the supply chain (Lee et al. 1997). In the literature on supply chain disruptions, the parallel notion of the reverse bullwhip effect states that shocks caused by supply disruptions can amplify as they propagate downstream, in part due to dynamics of panic buying and ordering behavior (Rong et al. 2008, 2017). Hence, the impact of pandemic can be different from other typical disruptions as the global supply chain is obstructed upstream, downstream, and midstream. Lee (2002) discusses various strategies to tame the bullwhip effect arising from demand and supply uncertainties.

Based on the analytical approach developed in this line of literature, we compare and contrast alternative network strategies using network optimization and simulation analysis. For more analytical models in supply chain disruption, please see the review study by Snyder et al. (2016). While prior studies offer a valuable basis for formulating design and operations strategies for facing the pandemic, we note that the COVID-19 disruptions are fundamentally different from other disruptions considered in the above studies. Our contribution is to extend the supply chain disruption literature by investigating principles that are particularly robust against the pandemic-induced disruptions.

3. RESEARCH METHODOLOGY

Our main research methodology is based on discrete-event simulation (Banks et al. 2020) to analyze the dynamics of alternative supply chain network designs under various pandemic-induced disruption scenarios, and to perform risk analysis. In the following sections, we shall discuss a comprehensive disruption management strategy comprising several phases: Contain, Delay and Mitigate, Recover, and Redesign.

To simulate disruption dynamics, we make use of the data on confirmed COVID-19 cases from the World Health Organization (WHO), and database on lockdown measures from the government response tracker from the University of Oxford (Coronavirus government response tracker: https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker). In particular, upward trends in confirmed cases and lockdowns would lead to commensurate drops in processing capacities along the supply chain as well as demand. The lockdown information serves as an input that determines the time-to-recover after the disruption, and the simulation analysis will compute key performance measures such as inventory levels, time-to-survive (the duration in which the supply chain survives by meeting the required demand) after the disruption, total costs at each stage in supply chain.

To assess the fundamental dynamics of a multi-stage supply chain, our simulation adopts a variant of the classical beer game setting. The specifics of operational policy and cost structure (e.g., inventory order policy, lead time, production cost) are described in the appendix. A supply chain structure in the simulation model is represented in a binary tree network with three layers: the final product at the assembly level requires two main components from the Tier-1 suppliers that, in turn, require two types of raw material inputs each from Tier-2 suppliers.

To examine the temporal and spatial impact during the COVID-19 pandemic, our analysis first considers representative network configurations spanning North America (U.S.), Asia (China), and Europe (Germany). Then, in analyzing optimal post-pandemic redesign strategies, we consider a large sample of alternative network configurations generated by randomly simulating the geographical placement of each node in the network. We examine various network design strategies such as flexibility, preparedness, and agility (which will be introduced in Section 4.3) under various pandemic scenarios. The simulation procedure is summarized as follows.

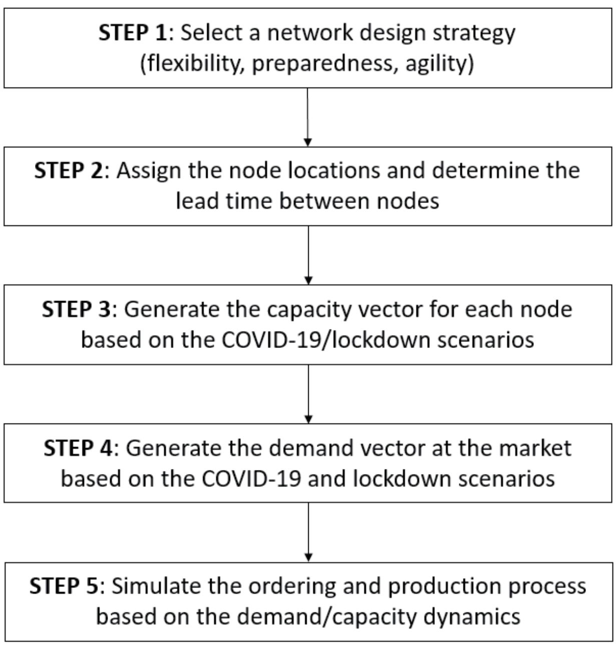

Figure 1. Simulation procedure summary

4. PHASES OF SUPPLY CHAIN RESPONSE TO COVID-19

When dealing with global supply chains faced with uncertainty, taming the bullwhip effect (Lee et al. 1997) is a key concern for firms. This is particularly important in studying the pandemic-induced disruptions, since an uptick in demand (e.g., panic buying amid the outspread of pandemic) will result in a supply-demand mismatch and its volatility increases towards the upstream of the supply chain. At the same time, a shock in supply capacity (e.g., production or shipment halt due to lockdown) may also result in a reverse bullwhip effect (Rong et al. 2008, 2017).

The recent incident of egg oversupply in Singapore is but one example that displays how vulnerable our supply chains can be to these adverse dynamics. Earlier this year, when the pandemic was just beginning to spread globally, eggs were in great demand in Singapore as households started to stockpile essentials facing the risk of a lockdown and potential disruption of import supply chains. Essential items were frequently missing on grocery shelves, and their prices skyrocketed in April. Facing this sudden surge in demand, egg importers hurried to ramp up supply. Yet, by the time the increased supply hits the market weeks later, demand had plunged since every household already had bought more eggs than they would need. In the end, the distributor had to dispose of more than 250,000 oversupplied eggs (Straits Times 2020). The wild swing from shortage to excessive supply highlights that a shock in the system, even without actual disruptions to supply, can already result in a brutal outcome.

To better visualize the dynamics of supply chain disruptions in global supply chains, take the example of a representative supply chain like Tesla's. Initially, Tesla procured some raw materials from its most upstream suppliers in China (e.g., rare earth minerals such as neodymium), where most of its battery and powertrain production, as well as final assembly, were located in the U.S. As the coronavirus first hit China early this year, the government decided to lockdown (first the city of Wuhan and then) the entire country soon after. In our representative supply chain, this would have resulted in a major disruption on raw material procurement, a shock that would propagate downstream and could eventually paralyze the entire system. The speed at which this shockwave would propagate depends on the amount of inventory held at the downstream stages and the pipeline. Obviously, safety inventory or safety capacity can play important roles in hedging against such supply chain glitches. However, as we shall see later, when faced with a long-lasting global pandemic like COVID-19, the mitigation provided by carrying safety inventory/capacity is limited, and a robustly designed network structure is essential to provide adequate protection against future disruptions of similar nature.

We assess the magnitude of damage due to COVID-19 on our illustrative supply chain using the simulation model. We consider the period between the first week of December, 2019 (Week 1) to the last week of August, 2020 (Week 40), where the confirmed new COVID-19 cases and lockdown status for the three regions are shown in Figure 2. As in the literature, we consider the inventory state as a proxy that reflects a supply chain's ability to balance supply and demand: in a healthy state where demand and supply are balanced over time, the inventory levels should only oscillate slightly around a healthy buffer level. Therefore, to assess the health status of the supply chain, we plot, in Figure 3(a), the inventory levels at the assembly, and the Tier-1 and Tier-2 supplier stages of the network. We can see that, before the pandemic outbreak, the supply chain was operating in a healthy state (Weeks 1-7). Then, in Week 8, the pandemic hit China (Hubei Province), who went on lockdown. As a result, the Tier-2 level output severely shrunk, and inventory levels sharply depleted. This causes a shockwave that propagates downstream to the Tier-1 and assembly levels.

Under the usual types of disruptions (e.g., natural disasters) studied in the literature, the shockwave results in amplified fluctuations and would take a while for the system to stabilize. In the case of COVID-19, however, the pandemic spread globally and the first lockdown in the U.S. (starting in Week 15) coincided with the lagged shock caused by the China lockdown. This indicates that the COIVD-19's impact on the physical flow of the supply chain incidentally overlaps with its epidemiological impact. Then, the U.S. went on extended lockdown. Therefore, despite China reopening in Week 20, the supply chain remained in a depleted state. The brief reopening of the U.S. (Week 23-26) achieved little more than causing more fluctuations upstream.

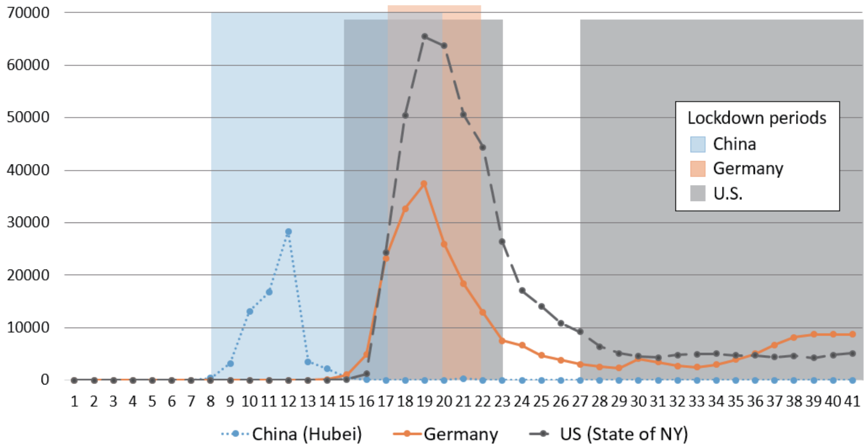

Figure 2. Weekly confirmed cases of COVID-19 and lockdown periods

The supply chain dynamics through the pandemic, as shown in Figure 3(a), reinforce the distinct nature of the COVID-induced disruptions compared to other disruptions that have been studied in the literature. In particular, rather than projecting a shockwave through the supply chain at one geographical region, the pandemic hits multiple points of the supply network following its epidemiological dynamics. Thus, to guard against disruptions of such nature, it is vital to devise a phased strategy that captures the propagation of both supply chain disruptions and the epidemiological spread of the pandemic. Next, we shall discuss the defense strategies for the containment, delay and mitigate, and recover (and redesign) phases.

4.1. Contain

The COVID-19 crisis is particularly different from other types of disruptions due to its unprecedented global scale and phased dynamics across countries. One of the key lessons we can learn from this pandemic is that many supply chains are in dire need for mechanisms to contain the initial hit that prevents the impact from spreading out across the global supply chain. Although global sourcing gives access to cheap resources with great degrees of flexibility, the extreme range in coverage exposes the supply chain to greater disruption risk—a disruption in one part of the supply chain quickly propagates through the entire system. Furthermore, containing the disruption locally is particularly challenging for COVID-19 because the pandemic is phased, and so different countries and regions are going through different phases of the curve. Thus, at the initial phase of the pandemic, it is critical to contain the disruption impact within a geographic region. If the adverse effect can be isolated within relatively small part of the network, the remaining network could remain operational for a certain period. As suggested in the literature (Mak and Shen 2012), whether or to what extent this can be done depends on the spatial design of the network.

As an illustration, consider again our representative Tesla-like supply chain. As discussed, Tesla's battery and powertrain production and final assembly were all located in the U.S. In 2018, Tesla opened Gigafactory 3 in Shanghai to meet the growing Asian demand for the Model 3. Doing so, Tesla was able to run a segregated supply chain that is almost independent of its U.S.-based counterpart; almost all components, including batteries and powertrain components, were locally produced in China. In our simulation model, this can be reflected by having all three tiers (assembly, Tier-1 and Tier-2 suppliers) located in China. Assessing the dynamics of this locally-contained network through the pandemic in Figure 3(b), we see that this network improves the Time-to-Recover (Simchi-Levi 2015) significantly. This is because its nodes are only shut down by disruptions in China and has room to recover quickly as the Chinese lockdown eases. In the original supply chain that spans China and the U.S., however, different nodes in the network are shut down at a different point in time and can collectively aggravate the global impact. In addition, such configuration will have long Time-to-Recover as it requires *both* its China and U.S. nodes to reopen. Therefore, the localized network in China, though motivated primarily by efficiency considerations in the case of Tesla, takes the character of a *containment strategy* that helps isolate the effect of disruption to its local region from the rest of the system. For pandemics that can be controlled within a relatively short period, as appears to be the case in China thus far, this strategy can prove valuable in protecting the supply chain's lifeline.

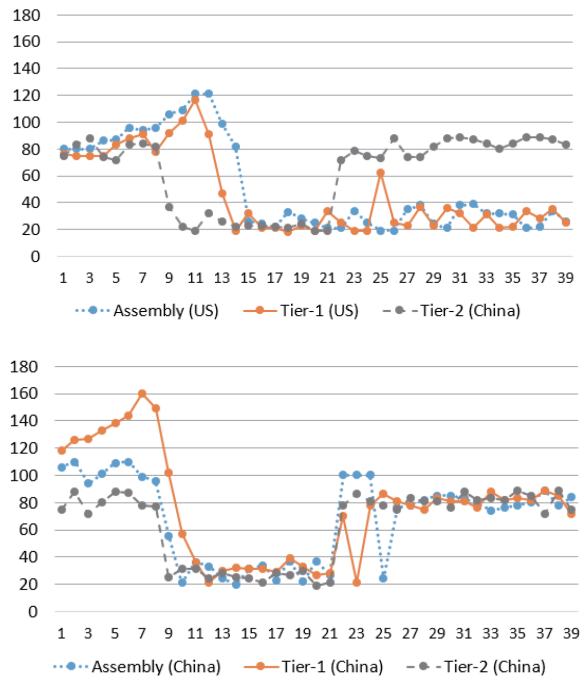

Figure 3. WInventory dynamics under COVID-19 for (a) the representative supply chain and (b) the China-contained supply chain

4.2. Delay and Mitigate

While the containment phase takes a spatial view on the supply chain, the delay and mitigation phase requires both spatial and temporal considerations. As evidence suggests that the pandemic may not subside quickly, containment may not be a viable option in the long run. Thus, the response should move on to strategies that focus on delay and mitigating the pandemic impact. In particular, we seek measures that help the supply chain absorb and soften the hit, such that damages are both deferred and minimized.

In the supply chain disruption literature, a variety of mitigation strategies have been investigated in depth (e.g., Tomlin 2006, Tang 2006, Chopra and Sohdi 2014). Of particular importance are measures that build extra slacks in the supply network in preparation for potential disruptions, such as carrying extra safety stock and investing in extra production capacity. Carrying safety stock (of the final product and/or intermediate components and raw materials) can help a network temporarily remain operational despite the cutoff of supplies from upstream. Likewise, adding slack production capacity at different stages of the network can help mitigate the disruption impact. The simulation model suggests that the mitigation strategy of incorporating both safety inventory and safety capacity effectively buys the network some time and delays the impact of disruptions; the shockwave of the lockdown took until Week 18 to hit the assembly stage as in Figure 4 (when stockouts of the final product start to occur), compared with Week 15 in Figure 3(a). Thus, this strategy improves the *Time-to-Survive* of the network (Simchi-Levi 2015). This delay in damage could be valuable if the supply chain can utilize this time cushion to activate other countermeasures (as we shall discuss in the next phase). Yet, as Figure 4 displays, we cannot expect the delay measure to remain effective for long, as the safety inventory eventually depletes, the slack capacity can no longer be utilized; and the shockwave continues to propagate. Furthermore, this strategy comes with the downside of maintaining higher inventory and capacity levels than necessary to meet normal demand.

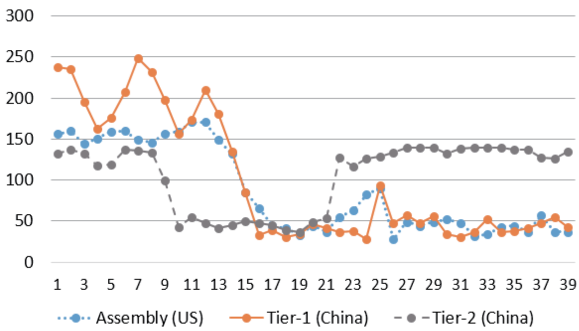

Figure 4. Inventory dynamics under COVID-19 with safety inventory and safety capacity

Delay and mitigation strategies can be vital in postponing and softening the disruption impact, and buy the supply chain valuable time to engage in countermeasures. While these could be sufficient strategies for short-term disruptions, such as the 2003 SARS pandemic in Asia that subsided within a few months after the initial outbreak, our simulation suggests that these remedies cannot be sufficient in countering the current pandemic-induced disruptions. This is a hard lesson that many supply chain executives are learning—that we are dealing with a different type of crisis unseen before. The depth and breadth of the distress caused by the pandemic necessitate a fundamental overhaul of network structures. As we eventually emerge out of this pandemic, therefore, we must not only recover from the damages but also carefully redesign our global supply chains, as we discuss next.

4.3. Recover (and Redesign)

When the pandemic eventually subsides, the world expects to recover from the losses and transition into the new normal. As supply chains have been disrupted and even shattered, the recovery effort will involve significant redesign and rebuilding of the networks. As much of a burden this is, it also provides a unique opportunity for firms to rethink their network structures to guard against future crises or even possible future waves of COVID. In this section, we shall discuss the design principles that underpin resilient network designs against the pandemic-induced disruptions.

To assess the performance and resiliency of alternative supply chain network designs, we consider two metrics: the supply chain's operating performances under normal (no pandemic) circumstances and under the pandemic. The former can be a proxy for the network's *cost-efficiency* and the latter a measure of its *resiliency*. In our simulation model, we devise a performance index that reflects these scenarios; see Appendix for details. The performance index is normalized at 100 for the most cost-efficient network configuration under no disruptions (the ideal case); and its value in any other scenarios can be interpreted as the percentage cost increase over the benchmark ideal case. Following the literature on supply chain network design, we consider the concept of *strategic fit* (Chopra and Meindl, 2018, Chapter 2): that improving a key metric (resiliency) naturally comes at the expense of cost-efficiency, and thus the optimal trade-off involves choosing a point along an efficient frontier that enables the supply chain strategy to best fit the firm's competitive strategy. In particular, network configurations along the efficient frontier dominate other (non-efficient) configurations in *both* the efficiency and resiliency metrics.

Figure 5(a) shows the efficient frontier of supply chain configurations with respect to the efficiency and COVID-resiliency measures based on the simulation of a large sample of alternative network configurations serving demand in the U.S. We find that the configurations on the top-left corner of the figure exhibit high efficiency under normal conditions but low resiliency, as the performance under COVID-19 deteriorates significantly. Upon closer investigation, we find that these configurations heavily rely on China, and are the most cost-efficient under normal conditions. Yet, as the pandemic strikes, these configurations are hit hard by lockdowns in China, due to the geographical concentration. To diversify away from these risks, moving toward the bottom-right portion of the efficient frontier offers improved resiliency (lower operations costs under COVID-19), at the expense of lower cost-efficiency under normal conditions. These configurations involve moving (part of) the supply chain to Germany, which, despite its higher processing costs (than in China), was less adversely impacted by lockdowns under COVID-19.

Somewhat interestingly, the efficient frontier does not include any network configurations with production sites located in the U.S., due to the relatively high production costs. While some have advocated to diversify the supply chains' concentration in China and to reshore as we recover from the pandemic, we find that only the diversification part of this strategy is supported by our model. Instead of reshoring, a natural alternative would be to consider relocating (part of) the supply chain to a third country with lower production costs, that is either closer to the market (e.g., Mexico), i.e., near-shoring, or has less exposure to COVID (e.g., Europe or even other Asian countries such as Vietnam).

4.3.1. Robustness as Core Design Principle. While the above well-illustrates the efficiency-resiliency trade-off, constructing a supply chain design strategy based on a specific pandemic instance will be risky—it overreacts to the currently realized pandemic scenario by suggesting to diversify from a low-cost region to one with low exposure to COVID-19. The danger is that such network designs may not be robust against other pandemic scenarios.

To tackle this issue, we employ the concept of *robustness*, one of the fundamental concepts dealing with uncertainty in operations research, that differs from the notion of reliability. In particular, a planning solution is robust if, under the most adverse environment, its performance deteriorates to a minimal extent (see, for example, Bertsimas et al. 2011). In view of the COVID pandemic, we need to design future supply chains that withstand not only the currently realized COVID-19 disruptions, but also the coming second (or further) waves, and even future pandemics associated with different diseases. Thus, while it was the case for COVID-19 that the impact was first felt in China and that the U.S. has been shut down for a longer period than Germany, it is unlikely that the same pattern or dynamics would repeat. At the time of writing, Europe is confronting a second wave of COVID, while cases in the U.S. seem to have plateaued and China has largely reopened.

To see the importance of robustness, observe in Figure 5(b) how the supply chain configurations on the efficient frontier identified in Figure 5(a) would change if we consider the worst case out of other possible pandemic scenarios (as opposed to the currently realized one). We see that the China-focused configuration performs similarly under the current and the worst pandemic scenarios, indicating the present scenario was already quite adverse for China; whereas the Europe-focused designs can deteriorate to similar (or poorer) performance levels under alternative hypothetical disruption scenarios or even a second wave.

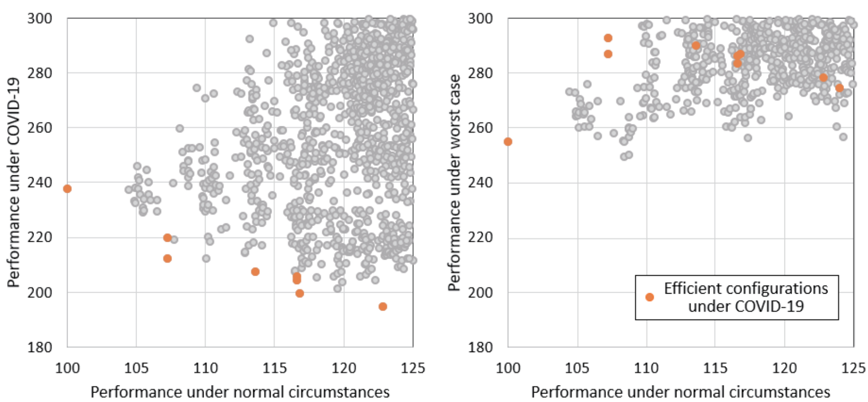

Figure 5. (a) Efficient frontier of supply chain configurations (colored in orange) under COVID-19 and (b) Efficient frontier for the worst-case scenario

This finding echoes with the suggestion of Simchi-Levi and Simchi-Levi (2020), that overreacting to the current pandemic (e.g., by reshoring) is not a panacea; Rather, firms should carefully stress-test the existing supply networks, identify vulnerabilities and reinforce them. In what follows, we shall discuss a few strategies to bolster the network design, namely, flexibility, agility, and preparedness.

4.3.2. Flexibility. Process flexibility is a fundamental concept in designing production systems. Under potential mismatch between product demand and production capacity, it is known that a small degree of flexibility, when carefully deployed in a long chain structure, can go a long way (Jordan and Graves 1995). The long chain refers to the production network configuration in which each product can be flexibly produced by a (small) number of plants, and each plant can flexibly manufacture a (small) number of products, such that all products and plants can be directly or indirectly linked in a long connected chain. In view of risk management, however, the long-chain structure requires a rethink. The effectiveness of the long chain stems from the connectedness of the network; on the flip side, any disruption instance in a long but lean chain exposes the entire system to risk. Thus, it is critical to build the right amount of redundancy in the flexibility network to ensure connectedness even as links and nodes are disrupted.

In any stage of a supply chain network, flexibility can be enabled by sourcing components or raw materials from multiple, geographically segregated suppliers in a flexible mix. Depending on the specific stage this is implemented, such sourcing flexibility could require tweaks in product architecture and incur higher logistics costs. Thus, flexibility is a form of strategic redundancy that would drive up costs under normal conditions, and it must only be deployed at strategic positions in the network topology.

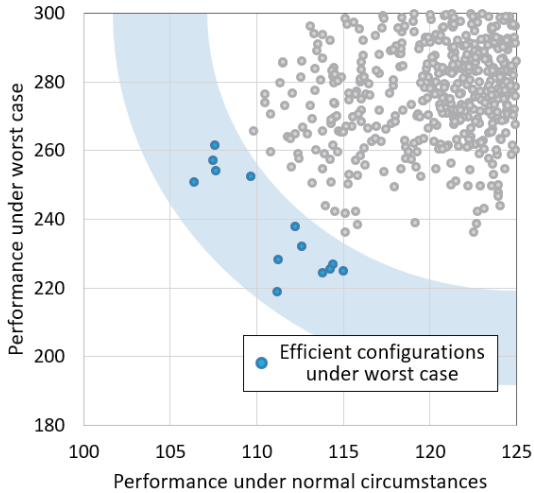

Figure 6. Efficient flexible configurations under worst case scenario

To explore the value of operational flexibility and its optimal placement in the supply chain, we simulated the robust efficient frontier for a large population of network configurations where such strategic redundancies can be introduced at randomly-deployed nodes of the network. As expected, the added flexibility improves the COVID-resilience at the expense of increased operational cost under normal circumstances. Figure 6 demonstrates the performance of the robust supply chain configurations identified in the efficient frontier in Figure 5(b). These configurations display superior performances over others, as can be seen by the frontier band in the shaded region.

With a closer investigation, we find that the network configurations form two clusters. The configurations in the top-left portion of the frontier band are generally the ones that concentrate flexibility at the most upstream (Tier-2 supplier) nodes; whereas those in the bottom-right region have flexibility deployed at the most downstream (assembly) stage. This is in line with the insight that flexibility is most effective when placed at the source of variability (Hopp et al; 2010), which are usually the two end layers in the supply chain. The most upstream layer has the most exposure to the disruption, since it has the largest number of nodes, and thus suffers most from capacity fluctuation (e.g., reduced labor availability and capacity under lockdown) due to COVID-19. In contrast, the most downstream layer suffers the most from the demand variation due to the pandemic situation. Given that demand uncertainty and supply uncertainty are the primary sources of the forward and reverse bullwhip effects, respectively, we find that providing protection through flexibility at both endpoints of the supply chain (in the form of dual sourcing) can be an effective strategy.

4.3.3. Preparedness. While supply chain resiliency has been widely embraced as a strategic imperative over the past two decades, the devastation caused by COVID-19 has still caught many supply chain executives off guard. In redesigning resilient networks, a crucial starting point is to identify the sources of disruption and assess the associated risk to the network. Such likelihoods of adverse events are difficult to estimate even with state-of-the-art analytics, due to the lack of data and rare prior occurrences.

In view of such uncertainty, it is important for supply chain executives to plan for preparedness. In particular, understanding the asymmetric nature of the impact of disruptions, executives shall favor over-preparation rather than under-preparation. Examples of preparedness includes securing emergency backup suppliers, backup plans for logistics/transportation, and various guidelines on operational policies in case of occurrence of unforeseen disruptions. While it is difficult to precisely measure risk exposure, the consequences of being under-prepared can be drastically more severe than the opportunity costs (e.g., in reduced operations efficiency) of being over-prepared (Lim et al. 2013). Here, over-investment in resiliency is not a conservative strategy; rather, it can lead to the optimal network design.

To *prepare* the network for future disruptions, one common hedging strategy explored in the literature, in addition to flexibility, is to link up with emergency outside suppliers (e.g., Tomlin 2006). Tang and Tomlin (2008) further shows the value of flexibility in mitigating various sources of supply chain risks. Although such an outside option will be typically expensive and may not provide sufficient capacity in case of a severe disruption, it can serve as a useful stopgap during the downtime. Our simulation result shows that such an arrangement improves the performance index under the worst-case disruption scenario by 15.4 (% of operating costs under normal conditions) on average. Further, we find that an emergency outside supplier is especially effective when coupled with operational flexibility deployed at the most downstream layer, where parallel assembly lines are operated in different regions and can flexibly step in for one another if needed. Such flexibility at the most downstream layer assures that some assembly capacity remains operational through the pandemic, and thus, one must ensure that component supplies feeding to this final stage are uninterrupted to make best use of such configuration. This is why having a backup supplier option for the assembly stage offers a strong complement with the downstream flexibility strategy.

4.3.4. Agility. Fostering agility, the ability to respond quickly in a cost-effective manner, is another useful strategy that hedges well against unexpected changes in supply chain (e.g., Lim et al. 2017, Acimovic et al. 2018). Supply chain agility includes proactive stocking policies in response to imminent disruptions and adjusting operational policies (such as procurement, inventory, delivery) to meet sudden changes in supply chain requirements in timely manner. Supply chain networks aided by digital technology can swiftly adapt their configurations to changes in demand and supply, thus highly effective in balancing operational efficiency and responsiveness. The key is to maintain a fluid network configuration rather than a static one. This concept is core to the distribution strategies of online retailers such as Amazon. In fulfillment operations, a key source of economies of scale is the savings in stocking costs by pooling inventory for different geographical markets, especially for long-tail products with low demand. However, an agile distribution network, where orders can be dynamically fulfilled by any facility, operates as one virtual entity that achieves pooling of stock digitally across the entire network.

In facing disruptions that propagate over supply networks, an important form of agility is the ability to quickly react to the disruption by, for example, proactively increasing the inventory level to counter the disruption before the impacts hit the local area. Our simulation study suggests that this form of agility can help improve the worst-case performance index by 7.1% (of operating costs under normal conditions) on average. Furthermore, the ability is most effective when coupled with the flexibility that targets the most upstream nodes. The reason agility works particularly well with upstream processing flexibility is that proactive stocking in advance of an impending disruption requires the upstream to remain operational at the initial stage of lockdowns. An effective way to secure upstream supply is by investing in upstream flexibility.

4.4. Implementation Remark and Managerial Insights

We have discussed three strategic elements for developing robust network designs through an extensive simulation study. The central theme of the study is to establish robustness in network design, one that will withstand not only the current but also other alternative disruption scenarios in the future. In what follows, we leave some implementation remark on the three strategic elements for developing robust network designs.

First, implementing flexibility involves building the optimal amount of slack, in the form of parallel processing capacity in segregated locations, at strategic positions of the network. Given the nature of pandemic that has caused supply and demand disruptions simultaneously, we must pay attention to both the forward and reverse bullwhip effects. The best positions for placing the strategic slacks through flexibility tend to be at the end layers of the chain.

Second, we find that a single strategy may not be sufficient considering the scope and scale of COVID-induced disruptions, and therefore, a careful pairing of multiple strategies will be needed in network redesign efforts. In Figure 7, we bolster each configuration along the efficient frontier based on the flexibility strategy (Figure 6) with agility and preparedness strategies. As discussed, preparedness strategy (arranging emergency suppliers) is better paired with flexibility deployed downstream, as shown in the bottom right cluster of the efficient frontier; whereas, agility strategy (proactive inventory control) is better paired with flexibility deployed upstream, as seen from the upper-left portion of the efficient frontier.

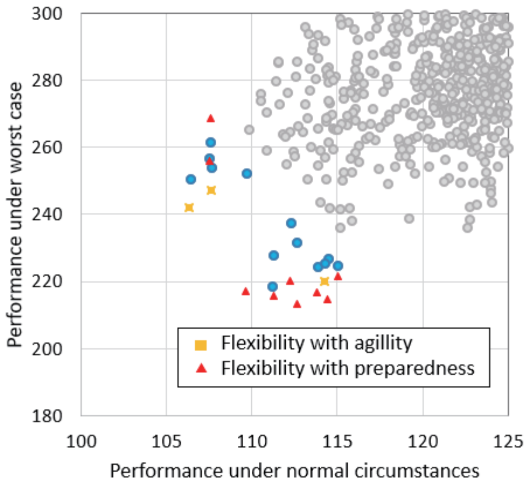

Figure 7. Efficient network configurations bolstered by optimal pairing of flexibility with agility and preparedness (superposed on Figure 6)

Below, we summarize relevant managerial policies of this research.

- The design principles must be based on potential disruption profiles rather than the currently realized scenario. We recommend that supply chain executives over-invest in supply chain robustness while cautioning against overreacting to a particular (current) pandemic scenario.

- No single remedy is sufficient to hedge against a global pandemic like COVID-19. Mitigation remedies such as containment and safety inventory/capacity can be effective in short-term, but a combination of well-coordinated strategies, incorporated at the design stage, is critical to guard against the pandemic-induced disruptions.

- Flexibility complemented with the strategies of preparedness and agility can be especially valuable in robust network. In particular, preparedness (securing emergency backup suppliers) is most effective when flexibility is deployed downstream; whereas, agility (proactive stocking policies in response to imminent disruptions) can be most helpful when flexibility is deployed upstream.

5. CONCLUSION

As modern supply chains have become increasingly global and interdependent in the last few decades, they have also become more vulnerable to the threat of disruptions. While our discussion has primarily focused on the restructuring of supply chain network, firms must also rethink strategies on other aspects of supply chains. For example, the pandemic will likely be an impetus for the development of smart and automated factories and warehouses utilizing robots. Using less on-site labor fosters social distancing and reduces the risk of factory shutdowns due to COVID-19 outbreaks. Overall, those firms who are the early pioneers of supply chain digitalization (e.g., Amazon, Alibaba, and LEGO) have been outperforming the market by substantial margins. This is a signal that digital transformation in supply chain management is inevitable.

Our modern, globalized economy has never experienced a crisis like the COVID-19 pandemic before. And, understandably so, no supply chain is ever designed to face this scale of disruption. While it is unclear when (or even if) the pandemic will end—we might as well be prepared for a new normal where we coexist with the Coronavirus—one thing is clear: we must consider creative strategies for our future supply chains. The silver lining here is that everyone is at the same starting line—just as scientists and pharmaceuticals are racing to develop effective vaccines against the Coronavirus, firms are also racing to devise the most effective disruption-immune strategies to emerge as winners in the post-COVID era. The supply chain executives must use this opportunity to take a fresh look at their supply network and devise creative strategies to improve robustness in their systems.

Appendix: Design of Simulation Study

Below we describe the design of the simulation study we conducted for this research. We considered a simplified supply chain structure represented in a binary tree with three levels, as shown in Figure 1. To assemble the final product (node 0), the firm needs two main components from tier-1 suppliers (nodes 1 and 2), which in turn require two types of raw materials each from tier-2 suppliers (nodes 3 and 4, and nodes 5 and 6, respectively). Although the supply chain structure is fixed throughout the entire simulation study, we consider that the location of each node can vary (either predetermined or simulated) among three different continents: North America (U.S.), Asia (China), and Europe (Germany).

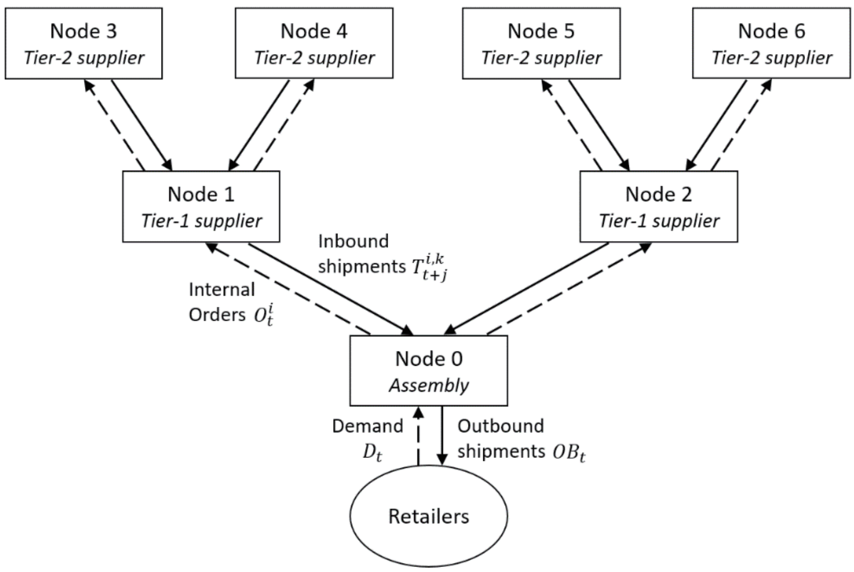

Figure 8. Supply chain network and assembly process

Based on the network structure, we utilize the discrete event simulation approach (e.g., Banks et al. 2005) to investigate the impact of COVID-19 on the supply chain.

To simulate the ordering and production dynamics according to the network structure, we define the following notation:

- S_t^i , C_t^i , I_t^i , O_t^i , P_t^i are the base stock level, production capacity, on-hand inventory (at week end), order quantity and production quantity at node i at Week t.
- $R_t^{i,k}$ is the component inventory held at node i, supplied by parent node (supplier) k at time t.
- $T_{t+1}^{i,k}$ is the inventory in-transit to node i from its parent node k, which will be received by node i in Week (t+j).
- $LT^{i,k}$ is the shipping leadtimes from node i's parent node k.

In addition, there is a production leadtime of one period for each node.

- B_t is the shortage (backorder) level for the final product of the supply chain.
- D_t is the demand for the final product in Week t.
- OB_t is the outbound shipment for the final product in Week t.

Then, for node 0, the order quantity in Week t is given by:

$$O_t^0 = S_t^0 - I_t^0 - \min_k\{ R_t^{0,k} \} + B_t^0 .$$

For every other node i where $i \neq 0$, its order quantity in Week t is given by:

$$O_t^i = S_t^i - I_t^i - \min_k\{ R_t^{i,k} \}.$$

After placing order to the upstream, each node fulfills downstream demand. The outbound shipment, i.e. the fulfilled sales of supply chain, OB_t is equal to

$$OB_t = \min (D_t + B_{t-1}, I_t^0).$$

Then, the in-transit inventory will be updated. For j < $LT^{i,k}$, we have $LT_{t+j}^{i,k} = LT_{(t-1)+(j+1)}^{i,k}$. Moreover, let f(i) be the index of a child node of node i. Then for node i where i>0, we have

$$T_{t+LT^{f(i),i}}^{f(i),i} = \min(O_t^{f(i)} , I_t^i).$$

After outbound shipment, production at node i starts and production quantity P_t^i is equal to

$$P_t^i = \min (C_t^i , S_t^i - I_t^i , \min_k\{ R_t^{i,k} \}).$$

Then, we record the inventory status at the end of the Week. At node 0, the on-hand inventory and backorder levels are updated by:

$$I^{0}_{t+1} = \max (0, I^{0}_{t} - D_t - B_{t\text{-}1} + P_t).$$

$$B_t = \max (0, D_t + B_{t\text{-}1} - I^{0}_{t}).$$

For node i where i>0, the on-hand inventory is given by:

$$I^{i}_{t+1} = \max (0, I^{i}_{t} - O^{f(\mathrm{i})}_{t} + P^{i}_{t}).$$

Lastly, we update the component inventory ready for the production, supplied from node i's parent suppliers at time t.

$$R^{i,k}_{t+1} = R^{i,k}_{t} + T^{i,k}_{t} - P^{i}_{t} .$$

In the basic setting, the base stock levels are set to be 250 at the assembly node (0), 300 at the component production nodes (1, 2), and 90 at the raw material nodes (3, 4, 5, 6). The production cost is considered to be the cheapest in China and the most expensive in U.S. The transportation lead time is considered one week between the same continent and two weeks between different continents. The transportation cost is proportional to its corresponding lead time.

The production of components and raw materials are subject to random yield to reflect the uncertain nature of production (e.g., random yield of wafer fabrication in a semiconductor supply chain or battery production in an electric vehicle supply chain). The maximum production capacity at each node is set to 100 in the normal state, but is reduced depending on the severity of coronavirus spread in each region. We capture such impact of COVID-19 in two ways. First, we assume that the production capacity at each region is affected by the number of newly confirmed COVID-19 cases each week. We use the weekly confirmed cases prior and after the lockdown periods and reflect the values on the available capacity at each node. In particular, we use the newly confirmed case in the first week of lockdown of that region as a baseline capacity denoted as $N^{k}_{lockdown}$ where $k \in \{$ china, Germany, US $\}$. The capacity of week i is then set to 100 - 20 $N^{k}_{i} N^{k}_{lockdown}$. Second, in case the lockdown is declared, we assume that the production drops significantly from its baseline capacity. Specifically, we consider that the capacity at each node is set following the uniform distribution between 20 and 40 during the state of lockdown. We consider demand to be originated in the U.S. In non-lockdown periods, demand is randomly drawn from a uniform distribution between 70 and 80. During the lockdown periods, demand is reduced by 10%.

The lockdown periods and durations for each location vary considerably. We chose a representative city from each country and simulated the lockdown status. Specifically, the lockdown period of China follows the status of Hubei Province (which hosts Wuhan where the first imported COVID-19 case was reported), using data obtained from Hubei Province government website. The lockdown periods for the U.S. factories are set based on the New York state, while the lockdown periods for Germany are set based on its national policy. The lockdown periods are obtained from the government response tracker from the University of Oxford.

Based on the baseline setting, we have made the following variations to further simulate situations of our interest. First, to consider the effect of flexibility, we consider a dual sourcing policy. The production of a node is then split into two sub-nodes (sites), located in different (randomly assigned) continents, to avoid a complete shutdown in case of a disruption. We assume that the capacity and base stock level of the node are equally split between two sub-nodes.

In addition, in simulating the preparedness strategy, we consider the availability of emergency outside suppliers with limited capacity (20 units) during lockdown periods. For the agility strategy, we allow nodes to proactively alter their ordering and production policies (increase the base stock levels) when a lockdown starts in any of three countries.

In order to evaluate the performance of a supply chain, we calaculate a composite performance (cost) measure that comprises of the costs of production, shipping, carrying inventory, and backorder (shortages). The index is normalized to 100 for the most cost-efficient network configuration under normal conditions (i.e., no disruptions), which consists of a network configuration with all production sites located in China. Then for any other configuration (and under COVID disruptions), we compute the performance measure as the percentage cost increase over this ideal benchmark.

As discussed in Section 4.3, we evaluate the peformances of supply chain configurations under the robustness principle, i.e., based on the worst-case pandemic scenario. While the realized pandemic trajectory of COVID-19 first hit China, followed by the U.S. (longer lockdowns) and Germany (shorter lockdowns), we also consider all alternative permutations where these sequences and magnitudes are flipped (e.g., the pandemic first hits Germany, followed by U.S. and China). Under the robustness principle, we evaluate each configuration based on its *worst-performing* (highest cost) scenario.

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