Achieving Supply Chain Efficiency and Resilience by Using Multi-level Commons

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We offer the notion of ‘commons’ at different levels — within company, private across company, and government sponsored across industry sectors — and discuss how the creation of such commons enabled firms to be both efficient during normal times and resilient against the disruptions resulting from COVID-19. At the same time, there are many proven strategies providing resilience in supply chains. For instance, companies that used multiple channels to improve efficiency when facing day-to-day demand-and-supply variations found that the structure also offered resilience without additional cost when COVID struck. We discuss how the presence of commons lowers the cost for firms to adopt such resilience building supply chain strategies. We discuss factors that impact the creation of these commons and conclude with a number of questions to guide further research into the role of industry commons in facilitating supply-chain resilience.

Key words: Supply chain risk management; supply chain disruption; COVID-19; resilience; industrial commons

INTRODUCTION

COVID-19 has disrupted the flow of materials, information, and funds in supply chains in many industry sectors. Lockdowns caused disruptions in the flow of material and information resulting in sharp demand declines as well as supply shortages. Fund flows were disrupted when firms refused to offer trade credit to their customers, resulting in sudden increases in working capital needs for many firms. Despite these disruptions, some companies managed their supply chains through the pandemic successfully.

To explain why some firms' supply chains managed to thrive during the pandemic and others did not even survive, we present the concept of 'commons' at multiple levels. The notion derives from shared land in an English village where all the people in the village can graze their sheep. In a similar vein, we consider commons for a supply chain to be a set of pooled resources for the flow of information, product, or funds. The resources might be pooled at different levels — within a company, within an industry, or across multiple industries. Regardless of the level, firms can use access to some commons to improve both efficiency and resilience of their supply chains.

The notion of having multiple channels for the flow of information, product, or funds is important in supply chain design. Companies that developed multiple channels to improve efficiency when facing day-to-day demand-and-supply variations, found during COVID that the structure offered resilience with little additional cost. For instance, Walmart used the combination of online as well as in-store sales to serve customer efficiently during COVID. We argue that the presence of appropriate commons lowers the cost for firms to use multiple channels.

The use of commons across these multiple channels is key to achieving supply chain efficiency during normal times and resilience to disruption. In the above example, Walmart used its website and stores as a in-company commons for serving both channels, allowing it to pivot store sales during COVID to online ordering and curbside pickup. Besides large companies such as Walmart that can afford to invest in multiple channels and commons, small companies can also benefit from commons provided by third parties. For instance, small retailers in a particular region could outsource their online deliveries to third parties, and thus create an online channel at low cost that provides them increased sales in normal times and resilience during a pandemic. Many small retailers used the commons provided by third party transportation and warehousing providers such as Alibaba or UPS who enabled additional sales channels for these retailers during COVID.

Besides facilitating multiple channels of flow, the availability of commons also lowers the cost of implementing established strategies to build resilience such as investing in flexibility, caution, risk mitigation inventory, or reserve capacity. This is particularly helpful for small firms who could not afford to invest in resilience in the absence of commons.

In the rest of the paper, we first describe commons at the three levels mentioned earlier. Then, we describe disruptions and variations in the supply chain, also at three different scales. We also present different contextual, demand, and supply dimensions across which these disruptions and variations occur. After that, we show how firms use multiple channels for the flow of information and products to achieve efficiency when dealing with normal variations in demand and supply and resilience when faced with disruptive changes to demand or supply. We also discuss how the presence of commons across these channels allows firms to build resilience at low cost. We also discuss how the presence of suitable commons lowers the cost of implementing several resilience building supply chain strategies. Across company commons are especially helpful for smaller firms to create resilience at low cost. Next, we describe the factors that enable the creation of commons at different levels, whether by private parties or the government. Finally, we list research questions on building and using commons.

THREE LEVELS OF 'COMMONS'

In this paper, we view commons as a set of pooled resources that enable a more efficient flow of information, product, or funds in supply chains than would be possible otherwise. By facilitating the creation of alternate channels of flow, commons also provide resilience in case one of the channels is disrupted. Commons can be considered at three levels: *in-company commons* — shared across product lines or channels or different business units within a company — *private across-company commons* such as 3PL or shared warehousing offered by the private sector, and *government-sponsored commons* that are funded by the government. We discuss these levels below.

Level 1: In-company commons

Firms with scale can aggregate alternate channels of information, product, or funding flow by taking advantage of shared resources. For example, Amazon's information infrastructure allows the firm to view its network of multiple warehouses as one 'virtual' warehouse to fulfill customer orders. If a particular item is not available in the nearest warehouse, an alternate warehouse can be used for fulfilment. The information infrastructure backed by a network of warehouses creates a fulfillment commons that efficiently pools normal demand and supply variations. When Amazon had to shut a warehouse down because of COVID, this fulfillment commons also provided resilience as alternate warehouses and delivery services could serve the customers who were served by the affected warehouse earlier.

During COVID, Walmart pooled its online order-taking, Walmart.com, with in-store sales to allow customers to order online for curbside pick up from its retail stores. The online system served as an information commons for both online shoppers and those who had earlier done shopping in-store. The stores served as a fulfillment commons for both types of customers. Although Walmart had set up this structure to improve efficiency prior to COVID, it naturally provided resilience against COVID-caused shopping disruptions.

Level 2: Private across-company commons

A commons may aggregate across firms, including competitors, by sharing resources to manage the flow of information, product, or funds. Such a commons allows for greater efficiency for all companies using the commons via lower fixed costs, lower variable costs, and optional additional capacity. The improved efficiency often provides sufficient incentive for the creation of private commons. Such private commons may be created by third parties, a partnership of competitors, or a collaboration across industries. Alibaba, UPS, and Federal Express are examples of private third parties that provide e-commerce delivery and storage resources that are shared across competing firms. These third party commons improve efficiency in the face of normal variation but also provided significant resilience during COVID. These commons are particularly valuable for smaller firms who could not afford to create additional sales (or procurement) channels without the commons.

Level 3: Government-sponsored 'industrial' commons

The third level of commons is what Pisano and Shih (2009) refer to as 'industrial commons'. They argued that industrial commons could rejuvenate manufacturing in the US via some shared resources for industry as a whole. Western North Carolina has sought to develop an industrial commons (`theindustrialcommons.org`) to "found and grow interconnected enterprises that solve industrial problems for businesses and workers and manufactures hope for the people of Western North Carolina." The government plays a central role here by providing funds or infrastructure to facilitate the effective functioning of supply chains across companies and geographies. Government investment is needed because the investment required for the commons at this level is either too large for private companies or the benefits are too broadly shared.

Industrial commons can range from holding stocks to having domestic manufacturing capacity to creating capability in general (Sodhi and Tang 2021b). The strategic petroleum reserve is an inventory-based commons sponsored by the United States government that provides resilience to competing firms who otherwise could not afford this inventory to mitigate disruption risk. The joint effort by the "Quad" of countries is an example of a commons with funds, capacity and capability. The U.S. and Japan will provide funds, India the manufacturing capacity, and Australia the distribution of COVID vaccines to south-east Asia.

VARIATIONS, DISRUPTIONS, AND EXTREME SUPPLY CHAIN CONDITIONS

Normal *supply chain management* entails a company managing the flow of products, information, and funds to ensure supply efficiently meets demand despite normal day-to-day variations in supply and demand (Chopra and Sodhi 2004). *Supply chain risk management* deals with the risk of disruptions that can cause a sharp and large mismatch of supply and demand in a supply chain (Chopra and Sodhi 2014). There is yet another level: COVID, for example, affected many companies and industries worldwide. The shock along the flow of products, information and funds was not only big for many companies, but also the impact was spread across most companies and much

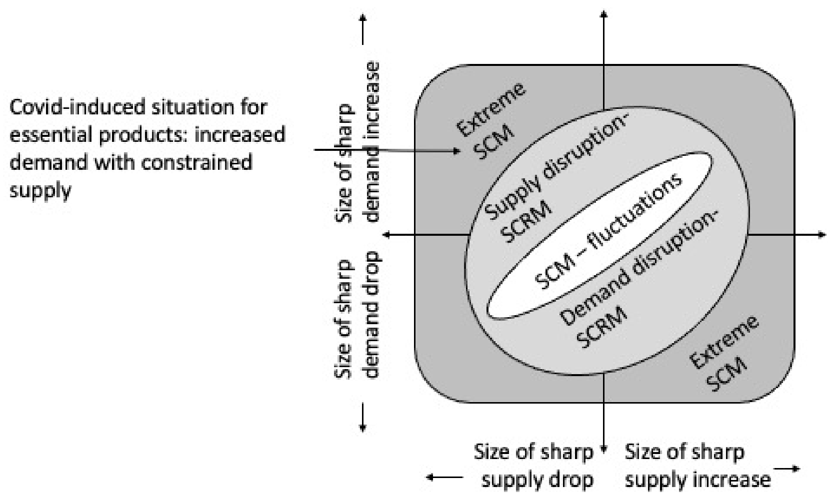

Figure 1 **Normal supply chain variations, supply chain risk, extreme supply chain conditions.** *Source*: **Sodhi and Tang (2021c)**

of society. Matching demand and supply under such difficult circumstances requires what Sodhi and Tang (2021c) call *extreme supply chain management* (Figure 1).

Let us see how COVID-19 disrupted product, information, and funds flow for entire industries like the airlines and supply chains in entire regions around the world.

1. **Flow of products**

(a) *Supply certainty*: The pandemic created significant supply uncertainty especially in the first six months of 2020, for both household goods and other supply needed by companies.

(b) *Availability of labor*: During COVID, many US meat processing plants had to temporarily shut down because of workers getting infected (Telford 2020).

(c) *Geopolitical stability*: Geopolitical risk was already on the increase in 2019 and only got amplified by the pandemic. For instance, after the border skirmish with China in mid-2020, India imposed additional scrutiny of imports of electronics components from China. The US government has limited Huawei and its suppliers' access to American technology and software, disrupting

Huawei's 5G equipment development. In retaliation, the Chinese government has threatened to restrict the supply of rare earths to disrupt the US aerospace-and-defense sector.

2. **Flow of information**

(a) *Supply chain visibility*: In normal SCM, we know (or should know) who the suppliers are. Covid-19 caused severe concerns about the provenance of some critically needed goods. Although the Food and Drug Administration (FDA) knew that 13% of brand and generic API (Active Pharmaceutical Ingredient) manufacturers were located in China, it did not know the actual volume of Chinese APIs in the US market. Dai and Tang (2020) reported that over 1,300 Chinese medical suppliers, including 217 N95 mask manufacturers, used false addresses and nonworking numbers in their registrations with the FDA.

(b) *Demand certainty*: During COVID, lock downs resulted in demand disappearing from certain brick-and-mortar channels for the lockdown period.

(c) *Channel stability*: COVID created an unprecedented shift in demand across existing channels for various products. For instance, home delivery as a channel grew multi-fold in 2020.

3. **Flow of funds**

(a) *Reliability of financial flows in supply chains*: The normal functioning of supply chains needs reliable financial flows; otherwise, we get into the situation seen in the 2008-09 financial crisis that disrupted many supply chains. During COVID, Auto manufacturers such as Honda, Jaguar, and Volkswagen saw financial difficulties, and retailers such as Neiman Marcus Group Inc., and J.C. Penny in the US and Arcadia and Debenhams in the UK filed for bankruptcy.

(b) *Availability of trade credit*: During COVID, many suppliers retracted their trade credit offers to their B2B customers due to a perceived increase in the risk of buyer default.

Next, we discuss how the use of appropriate commons helps manage disruptions and variations along one or more of these dimensions.

COMMONS AND SUPPLY CHAIN RESILIENCE

A suitable commons is helpful in managing variations or disruptions in the flow of products, information and funds of a supply chain. *In-company commons* are typically built by large firms

		The benefit of commons to an organization facing...		
Level	Type of commons	Normal variations	Disruptions	Extreme conditions
Level 1	In-company commons	Improved efficiency for company, with fixed costs shared across products, channels, or business units	Some resilience to the company at no extra cost	Some resilience to the company at no additional cost
Level 2	Private across-company commons	Improved efficiency for all companies sharing the commons with setup costs incurred by a third party or shared by these companies	More resilience for individual companies at low additional cost	More resilience at low additional variable cost to any one company
Level 3	Government-sponsored commons	Increased efficiency for most sectors with high setup cost incurred by the government	Most resilience for companies at low variable cost	Most resilience at low variable costs

Table 1 Value of commons for effectiveness and resilience against different levels of variations and disruptions

to efficiently deal with normal flow variations. They do, however, also provide some resilience to disruptions and extreme conditions. *Private across-company commons* are typically designed to allow small firms to efficiently deal with normal variation or to allow larger firms to efficiently deal with more extreme variation. These commons also provide all these firms with resilience in the face of more extreme disruptions. *Government sponsored commons* are typically designed to provide resilience under extreme conditions. They are expensive to set up – reducing the incentive for private parties to set these up – and designed for extreme disruptions. **Table 1** summarizes the roles played by the three levels of commons when dealing with different levels of variation and disruption.

Resilience with Level-1 'in-company' commons

Whereas Target and Walmart reported record quarters in 2020 at the height of the pandemic, many other retailers had some of their worst quarterly results. True, Walmart and Target benefited from being declared as 'essential' at the start of the COVID crisis, thus allowing their stores to stay open despite lockdown. Still, the ability to use multiple channels afforded by their omni-channel structure allowed them to capture demand and fulfill orders, enabling these companies to prosper during COVID.

Both Walmart and Target had created the omni-channel structure prior to COVID for improved efficiency under normal conditions. The omni-channel structure used a shared information commons for both home delivery and pick up orders and a shared store commons for both in-store shopping and store pick up. With the multiple channels for the flow of information, product, and funds, the omni-channel structure also proved resilient when COVID hit. Multiple channels can be expensive and can only be justified by a company either if it has significant scale or if it has access to shared resources for at least one of the channels. Small retailers typically cannot afford to implement an omni-channel strategy unless they have access to a commons shared across multiple firms, likely offered by a third party.

Resilience with Level-2 private across-company commons

Third-party logistics providers serve as Level-2 private across-company commons by offering information- and product-flow-related services for competing firms. During normal times, these shared resources allow the third parties to serve these competing firms more efficiently than the firms could on their own. During COVID, shared third-party capabilities such as logistics provided resilience by allowing firms to create alternate channels for information and product flow, allowing business to continue despite one channel or another having been disrupted.

Such shared resources provide a much larger proportionate benefit to smaller firms compared to larger ones because, unlike larger companies, smaller ones would not be able to afford the use of more than one channel in the absence of commons. Thus, the presence of such commons allows small firms to gain both efficiency and some resilience at low cost. It is for this reason both UPS and Federal Express increased their focus on serving smaller firms during the COVID disruption. Other examples of private across-company commons include contract manufacturers, and platforms that can be used by firms for order-capture and fulfillment.

Resilience with Level-3 government sponsored commons

It is not economically viable for individual firms or private third-party players to create resources that provide resilience under extreme disruptions like COVID-19 when the business and social impact of the disruption is both significant and correlated. For such a rare but extremely disruptive setting, a government-sponsored commons can provide resilience. The strategic petroleum reserve is an example of a government sponsored commons designed to help firms deal with extreme supply disruptions.

No individual hospital chain or private player could afford to carry enough ventilators in inventory for use in the next pandemic and nor could firms afford to carry sufficient reserve production capacity on call to produce ventilators when needed. The actions of the U.S. Government in response to ventilator shortages with the auto industry and ventilator manufacturers during March-Aug 2020 offers a possible model for a future commons. The government offered subsidies that led GM and Ford to retool some of their plants and those of their Tier-1 suppliers to produce ventilators. In the future, the government could offer annual premiums to supply chains that are flexible enough to produce multiple urgently needed products like ventilators and reserve capacity that can be used to produce these items when needed. During normal times, the capacity could be used by firms to produce items (such as cars) needed by customers. During a disruption, the capacity could pivot to produce needed items such as ventilators. The combination of the annual premium from the government and the available flexible capacity creates a government sponsored commons that can be used during a severe disruption. Sodhi and Tang (2021a,b) have proposed using inventory, capacity, and capability in lieu of an inventory-only stockpile such as the US Strategic National Stockpile.

COMMONS AND STRATEGIES FOR RESILIENCE AT LOW COST

The supply chain literature provides a variety of strategies that firms can use to build resilience. These *strategies for resilience* include:

1. Tailored sourcing
2. Omni-channel retail
3. Investing in flexible capacity and its use through better information
4. Investing in caution
5. Investing in risk mitigation inventory or reserve capacity

Several of these strategies are optimal approaches for large companies even when they ignore the possibility of disruptions and simply focus on efficiency by rigorously minimizing total incurred and avoided costs under normal variation. *Incurred costs* include the unit production, storage, and distribution costs, while *opportunity costs* include lost sales. In many of these instances, large firms use a level-1 in-company commons to efficiently create multiple channels for the flow of information, product, or funds. Happily, even though disruption risk may have been ignored in setting up these channels, the company benefits from getting resilience against disruptions that may affect one channel or another, but not all simultaneously.

Considerations of disruption risk typically suggest actions that increase resilience through additional investment in the supply chain or increased unit or marginal cost - see Kim et al. (2015) for the impact of network structure on resilience and Yildiz et al. (2016) for the trade-off between efficiency and resilience. Having an in-company commons in the supply chain can reduce the additional investment or the increase in unit or marginal cost, while still substantially increasing resilience for a large company. Such a company can benefit even more from Level-2 and -3 commons to build further resilience against even more extreme events at low cost. The benefit of an external commons is even larger for small firms who find it cost prohibitive to build resilience on their own. Therefore, Level-2 and -3 commons are particularly helpful for small firms as they enable these firms to create resilience in the supply chain at low cost.

Below, we discuss each strategy for resilience and how the availability of commons lowers the cost of building resilience.

1. Tailored Sourcing

Tailored sourcing entails at least two sourcing channels: the firm purchases the uncertain portion of demand from high-cost, high-response suppliers that are onshore or near-shore, and the predictable portion of demand from low-cost, low-response suppliers that may be offshore. Large firms often find that tailored strategies, created to minimize total cost, provide resilience even when the risk of disruptions was ignored when the sourcing strategy was devised. As Chopra and Sodhi (2004, 2014) note, tailoring designed to improve efficiency by lowering total cost also allows large firms to achieve some resilience for free.

Large companies often resort to tailored sourcing to efficiently meet the demand for different product categories based on their respective demand uncertainty or margin. Tailored sourcing is attractive in such a setting even when disruption probability is ignored (its attractiveness increases if disruption risk is included). Zara serves its European stores with fashion items (Fisher 1997) whose demand is difficult to predict from high-cost European suppliers with short lead times. In contrast, the company serves the same European stores with standard basic items with predictable demand using low cost suppliers in Asia with long lead times. Whether or not we include disruption risk, total cost is minimized by ensuring that the responsiveness of the source matches the uncertainty of product demand. Consequently, some resilience is obtained for free because it is unlikely that all suppliers, both local and offshore, would be disrupted at the same time. Craighead et al. (2007) provide empirical evidence that supply chains where suppliers are located far away from each other are less prone to disruptions than supply chains where suppliers are clustered together.

Models for tailored sourcing. A stylized model shows how tailored sourcing can minimize total cost even when disruption risk is ignored. Consider sourcing for a product whose demand has mean μ and standard deviation σ. Then, $cv = \sigma/\mu$ is the *coefficient of variation* of demand. The responsive supplier has unit cost C_r and lead time L_r and the cheaper supplier has unit cost C_c and lead time L_c with $C_r > C_c$ and $L_r < L_c$. Assume for simplicity that unit inventory holding costs h are the same for both cases. The total cost per unit (purchase cost + cost of safety stock) for the two suppliers then is:

$$COST_r = C_r + hz^* \sqrt{L_r}(\sigma/\mu) \tag{1}$$

$$COST_c = C_c + hz^* \sqrt{L_c}(\sigma/\mu) \tag{2}$$

Comparing the two costs we see that the responsive supplier may provide lower total cost, despite the high unit cost, for products with a high coefficient of variation, σ/μ. In contrast, the cheaper supplier may provide lower total cost for products with a low cv. Thus, a large firm like Zara with a wide variety of products may find it efficient to have a supplier portfolio that combines a cheaper supplier for basic items with predictable demand and a responsive supplier for fashion products with hard to predict demand. As we see from (1) and (2), this two-channel sourcing makes sense to improve efficiency even when the risk of disruption is not considered. However, such a portfolio naturally provides some resilience as not all channels are likely to be disrupted simultaneously in case of an untoward incident.

Other researchers have arrived at the same conclusion with different models. Avanzi et al. (2013) study optimal sourcing for the firm when there is demand uncertainty but no disruption risk. They found that when demand uncertainty is included, sourcing from the domestic supplier can be the better option even when the cost-margin of the domestic supplier is higher than the cost-margin of the offshore supplier. See also De Treville et al. (2014) in this regard. Similarly, Allon and Van Mieghem (2010) show that tailored sourcing that combines low-cost offshoring for the base level of demand and responsive on- or near-shoring for the variable portion of demand results in the lowest expected total cost when demand has a high enough baseload (likely for large firms) and a large enough variability without considering disruption risk. Such a supplier portfolio naturally provides some resilience for the large firm because local supply chains tend to be less prone to disruptions than global supply chains. Including a distance-specific disruption risk in (1) and (2), where the onshore source is more reliable, is likely to result in a greater use of the more reliable onshore source (see Habermann et al. (2015), who provide empirical evidence that supply chains with long leadtimes are more prone to disruptions than supply chains with short leadtimes).

How commons lower the cost of tailored sourcing. Consider Nike's flexible technology, Air Manufacturing Innovation or Air MI. A flexible plant serves as an internal commons that can be used to produce a wide variety of shoe styles. The availability of this commons has resulted in Nike increasing the insourcing and onshoring of flexible capacity within its tailored sourcing portfolio while also continuing to use cheaper offshore production. In 2020, Nike opened a new Air MI facility in Goodyear, Arizona in addition to similar facilities in Oregon and Missouri. Nike has targeted these flexible facilities to its newer models where the rate of innovation is high and demand is harder to predict while producing cheaper models at other low cost locations. The presence of the in-company flexible manufacturing commons facilitates tailoring of supply and provides natural resilience for a large player like Nike.

While Nike is a large company that can afford its own investment in flexible capacity, third parties have a significant opportunity to provide a commons for small companies. Contract manufacturers like Flex provide an industry commons to smaller shoe OEMs who cannot afford their own flexible facilities. Flex partnered with Nike to set up flexible facilities in Mexico. Now that the Nike-Flex partnership has ended, Flex can provide its flexible technology facilities for tailored sourcing to smaller shoe companies. The creation of such commons will make tailored sourcing affordable for smaller OEMs, increasing their resilience at low cost.

2. Omni-Channel Retailing

Large firms can create multiple channels on the sell side as well to improve order taking and fulfillment efficiency under normal variation. For example, Amazon, Walmart, Target, and Nike have omni-channel portfolios that efficiently align product, service offerings, and pricing across product-channel combinations to increase their *return on invested capital* (ROIC) (Chopra 2020) during normal times.

Although there were no considerations of disruption risk when these firms developed multiple sales channels, the omni-channel portfolio offers resilience against supply chain disruptions by allowing the retailer to call upon any available channel to capture demand and fulfill orders in the event of a disruption in one channel. Walmart saw a significant increase in sales through the online channel during the Covid-19 pandemic, which helped the firm to compensate for the decline in sales from walk-in stores[1]. Nike's digital sales allowed it to bounce back much quicker than its competitors from the COVID-related dip in sales. The investment in omni-channel portfolios before COVID by Walmart and Target helped them gain market share and profits during the COVID disruption by taking customer orders online to be fulfilled using curbside pickup. Seeing the benefits of curbside pickup in its omni-channel portfolio, Nordstrom increased the ability of customers to order online and pick their order up at any Nordstrom or Nordstrom Rack store during COVID.

The benefit of an omni-channel portfolio for resilience is clearer if we consider the fate of retailers who did not have such portofolios. Many apparel retailers, particularly at the high end, did not survive COVID or barely did so by not having an omni-channel portfolio. Luxury brands typically were highly dependent on walk-in stores for most of their sales. Even those with some online sales did not have a well coordinated omni-channel approach where demand and fulfillment could easily flow through any suitable channel and thus struggled during the pandemic. Japanese clothing retailer Cecil McBee, clothing company Onward Holding, and apparel company Sanyo Shokai are examples of such retailers.

Models for omni-channel retailing. A simple model illustrates how an omni-channel portfolio results when a large firm selling a variety of products aims to minimize total fulfillment cost during normal times in the absence of disruption risk. We consider the total cost of safety stock and transportation incurred by a firm to fulfill a customer request. The centralized online channel needs less safety stock while incurring a high transportation cost. In contrast, the decentralized brick-and-mortar channel requires more safety stock but incurs a lower transportation cost.

Consider a firm with n decentralized locations facing stochastic demand for a product with mean μ and standard deviation σ at each location. We assume demand to be i.i.d. across these decentralized locations. Let C be the cost per unit of the product and h the holding cost percentage. Let t_d

[1] Financial Times. Accessed at `https://www.ft.com/content/93fa27dd-7329-4780-9448-1dd09c678344`

(t_c) be the transportation cost per unit incurred when the product is sold from the decentralized (centralized) channel (with $t_c > t_d$). Let $cv = \sigma/\mu$ be the *coefficient of variation* of demand at each location. Demand at the centralized channel is assumed to equal the sum of demands across all decentralized locations (mean = $n\mu$, standard deviation = $\sqrt{n}\sigma$).

Let $COST_d$ be the annual holding and transportation cost incurred per dollar of product cost if the product is sold from the decentralized channel, and $COST_c$ the total cost if the product is sold from the centralized channel. The two costs are obtained as follows:

$$COST_d = n(z^*\sqrt{L}\sigma hC + \mu t_d)/(\mu C) = n(z^*\sqrt{L}h(\sigma/\mu) + (t_d/C)) \quad (3)$$

$$COST_c = (z^*\sqrt{nL}\sigma hC + \mu t_c)/(\mu C) = (z^*\sqrt{nL}h(\sigma/\mu) + (t_c/C)) \quad (4)$$

Comparing (3) and (4), we see that the centralized channel has lower total cost for products with uncertain demand (high cv) and high product cost relative to transportation cost (large ratio of C/t). The transportation cost for the *centralized* channel can be reduced by having pickup locations where customers can pick up their online orders. Diamonds and niche electronics are examples of products with uncertain demand and high value relative to transportation cost. By contrast, the *decentralized* channel has lower total costs for products with predictable demand (low cv) and low product cost relative to transportation cost (small ratio of C/t). Products like diapers and detergent fit this profile.

How commons lower the cost of omni-channel retailing. Unlike large companies, small firms cannot afford to develop internal capabilities to design and operate an omni-channel portfolio. Still, they can have higher sales and increased resilience at low cost if there is an industry commons available that supports omni-channel fulfillment. While the development of such commons had already started before COVID, it has accelerated during COVID. Amazon offers an omni-channel industry commons for small retailers with its online platform along with storage and fulfillment services. The availability of the Amazon commons has led firms like Thrasios, SellerX, and Heroes to buy up successful small brands on Amazon and build up conglomerates that use the Amazon commons to efficiently serve customers during normal times while becoming more resilient to potential disruptions[2]. Alibaba and Shopify are also creating omni-channel commons by adding warehousing and fulfillment services to their online platforms. UPS and Federal Express also offer such commons to allow small firms to effectively compete in this environment. With the growth in flexible warehousing technologies, the creation and operation of such commons becomes cheaper making it easier for small retailers to provide an omni-channel experience that is efficient during normal times and resilient during a disruption.

3. Investing in Flexible Capacity and its Use through Better Information

Another variant of the idea of multiple channels pertains to the manufacturing capacity of the company. Firms producing a wide variety of products or introducing a lot of new products can lower the total cost of providing variety by investing in flexible capacity. Flexible capacity, whether offering flexibility of volume or variety, is not free: companies have to invest in it, and unit costs are higher than for dedicated capacity. As in the previous two cases of multiple channels on the sourcing side or sales side, flexible capacity can not only help decrease total cost in normal times but also greatly increase resilience.

For example, Toyota has always located plants in each major market that it serves. Before 1997, capacity at each plant was dedicated to serving only its local market. This hurt Toyota when the Southeast Asian economy went into a recession in the late 1990s because of a local financial crisis. While the Asian plants had idle capacity, they could not serve other markets experiencing excess demand. To deal with independent demand fluctuations across markets, Toyota invested in flexible capacity to make each plant capable of serving at least one other market besides the local one. This investment in flexible capacity improved Toyota's ability to deal with normal demand and exchange rate fluctuations while also providing resilience in dealing with regional disruption.

The business case for investing in flexible capacity, even ignoring the risk of disruptions, improves as flexible production technologies get cheaper. A large firm can often lower total cost by using a

[2] Investors pour $1bn into buying up small merchants on Amazon, Financial Times, December 21, 2020

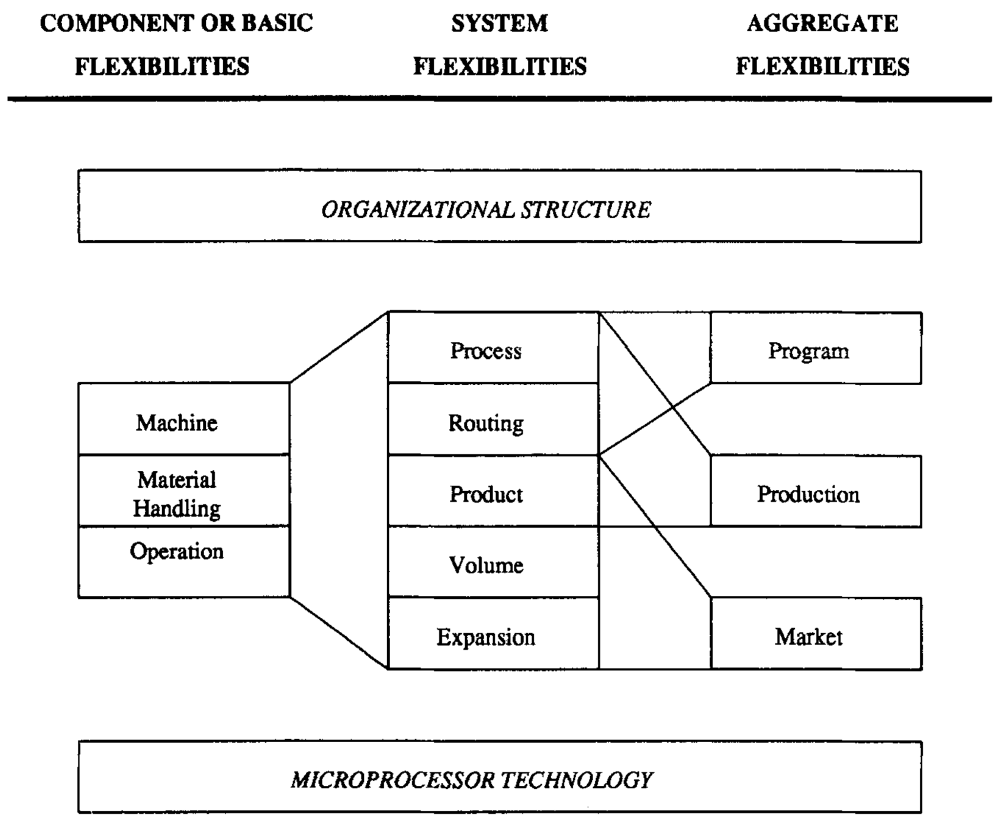

Figure 2 **Different flexibilities and their links.** *Source*: **Sethi and Sethi (1990)**

tailored production strategy similar to tailored sourcing described earlier: The firm uses *dedicated capacity* to produce *high-volume* products at low unit costs and *flexible capacity* to produce *low-volume* products at higher unit costs. Such a tailored production decreases total costs (incurred and avoided) while also providing resilience. As mentioned earlier, Nike produces some of its shoes using the more expensive flexible technology and others using traditional methods in low-cost countries. As flexible production technology becomes cheaper, Nike can install this flexible technology in each of its markets, thus regionalizing its supply chain for the more expensive shoes. At the same it, it can serve all of the global market by manufacturing goods with dedicated capacity in low cost countries for other shoes and apparel. For an overview of the different types of flexibility, refer to (Sethi and Sethi 1990) and Figure 2.

In recent years, firms have invested in advanced technologies such as AI or big data to improve demand forecasting. As shown in (Boada-Collado et al. 2020), the value of information from this improved demand visibility is particularly helpful when the supply chain has access to flexible capacity. This is again a situation where the availability of an information commons that helps firms improve forecasting at low cost, and a flexible capacity commons that helps firms react to the updated forecast, can help these firms simultaneously improve their efficiency and resilience. As mentioned already, Amazon's real-time information system and warehouse network is an internal commons that provides flexibility and resilience that allow it to reroute orders from other warehouses if a particular warehouse gets disrupted.

Modeling the link between flexible capacity and partial information. Jordan and Graves (1995) introduce the concept of *chaining* where capacity at each production node is flexible enough to serve a couple of markets, creating a chain. A chain requires a small amount of manufacturing flexibility while maximizing the benefit of this flexibility. While chaining is primarily designed to efficiently deal with normal variation, it naturally provides some resilience against disruption without any additional investments needed to achieve this resilience.

Boada-Collado et al. (2020) discuss models linking the value of partial information to the availability of flexible capacity under short term commitment contracts for capacity. Using a newsvendor network model they find that demand visibility and flexible capacity can be either substitutes or complements depending on the cost of flexible capacity. While demand visibility is always valuable, its value changes with the optimal investment in flexible capacity. When the cost of flexible capacity is very high, it is optimal to not use flexible capacity and commit only to dedicated capacity. Clearly, demand visibility is valuable in this situation. At the other extreme, when the cost of flexible capacity is very low, it is optimal to commit to a high level of flexible capacity. The high level of flexible capacity reduces the value of demand visibility below the case when the cost of flexible capacity is very high. In this situation, flexible capacity and demand visibility behave like substitutes with the high level of cheap flexible capacity absorbing any observed variation, thus making demand visibility less valuable. Between the two extremes, however, demand visibility is most valuable and flexible capacity and demand visibility behave like complements. Between the two extremes, it is optimal to commit to both dedicated and flexible capacity resulting in the highest value of demand visibility. Demand visibility allows the decision maker to efficiently use flexible capacity even in situations in which flexible capacity would be disregarded without visibility. In other words, demand visibility increases the marginal value of flexible capacity.

How commons can lower the cost of flexible capacity and improved information. While a large firm like Toyota can implement a flexible chain as described above, such an option for flexible capacity is too expensive for small firms. What is needed for small firms is regional flexible manufacturing capacity commons and suitable information commons. We anticipate growing availability of across company private commons for information and flexible capacity as such technologies become cheaper and more prevalent. The availability of 3D printing is likely to result in regional third-party 3D printing capacity commons. The availability of such commons' will lower the cost of flexible capacity for smaller firms without scale, allowing them to design tailored supply chains with high levels of both efficiency and resilience. Along with cloud computing (which is an information storage commons), we also anticipate a growth in artificial intelligence / machine learning (AI/ML) commons that uses data available to firms on the cloud to provide them with better forecasts and also a better ability to reconfigure their network in response to updated demand and supply information. The growth in such commons should allow smaller firms to improve their resilience at low cost.

4. Investing in caution against disruptions

The first step in building resilience against disruption is estimating the likelihood of a supply-chain disruption, which is a rare event. Companies may either *underestimate* or *overestimate* the risk of disruption. The consequence is not investing sufficiently in resilience in case of underestimation or investing too much in building resilience in case of overestimation.

An example of being overcautious paying off is that of the city of Seattle and the state of Washington dealing with the first COVID patient identified on American soil.[3] Given the extensive

[3] Frontline, Episode 16, Season 2020

people-and-trade contact between Seattle and China, the health authorities had expected the virus to eventually hit their city and state. They conducted an extensive simulation in early January to better prepare for cases when they arrived. The first patient arrived from Wuhan, China, in the middle of January and visited a clinic in Snohomish County complaining of COVID symptoms. The clinic was already prepared with testing gear, and after testing, he was sent home for self-isolation. When positive test results arrived in a couple of days from the CDC, the patient was picked up from his home using a fully equipped ambulance with an isolation pod and placed in isolation at a hospital within a couple of hours. The authorities had overestimated the likelihood of disruption and invested in possibly excessive preparation. The investment in appropriate assets (e.g. ambulances with isolation pods) and a good information infrastructure allowed them to respond effectively to COVID.

Overestimation, however, creates a leadership challenge because it requires upfront investment for a possible payoff in the future if a rare disruption were to occur. On the other hand, underestimation means not investing anything at all or investing very little. For example, even though the risk of a pandemic had been highlighted by scientists, many political leaders were reluctant to make costly preparations for the unlikely event of a pandemic. Even when the pandemic started to materialize and scientists advised politicians on the potentially negative outcome of the pandemic, some governments were still reluctant to take preventive measures due to underestimating the likelihood of such a negative outcome.

Modeling caution against disruptions. Lim et al. (2013) caution against underestimation. Over-investing in supply chain resilience by building flexible or redundant assets helps in the long term even if there is no disruption because the supply chain can use these investments to better deal with the normal uncertainties (such as demand fluctuations) it faces, i.e., in the form of a higher customer service level. In addition, the investment in resilience has significant value in the event of a disruption. By contrast, under-investing in supply chain resilience due to underestimation of the disruption probability means there is no additional investment in flexibility, excess capacity

	$\tilde{q}=0.03; \delta=0.25$			$\tilde{q}=0.03; \delta=0.5$			$\tilde{q}=0.03; \delta=0.75$			$\tilde{q}=0.03; \delta=0.9$		
r	$\hat{q}^*$	$\bar{F}(\hat{q}^*)$ (%)	$\bar{F}(\tilde{q})$ (%)	$\hat{q}^*$	$\bar{F}(\hat{q}^*)$ (%)	$\bar{F}(\tilde{q})$ (%)	$\hat{q}^*$	$\bar{F}(\hat{q}^*)$ (%)	$\bar{F}(\tilde{q})$ (%)	$\hat{q}^*$	$\bar{F}(\hat{q}^*)$ (%)	$\bar{F}(\tilde{q})$ (%)
1.25	0.0315	0.04	0.06	0.0376	0.22	0.47	0.0582	0.82	2.82	0.0872	1.57	7.31
1.5	0.0315	0.05	0.08	0.0375	0.27	0.57	0.0578	1.00	3.40	0.0859	1.91	8.68
2	0.0315	0.07	0.10	0.0374	0.33	0.70	0.0573	1.22	4.75	0.0846	2.31	10.21
5	0.0315	0.10	0.14	0.0372	0.49	1.02	0.0562	1.80	5.72	0.0815	3.32	13.74

Figure 3 **Optimal estimate and percentage increase under the worst-case scenario (Lim et al. 2013)**

or inventory that can help with normal variation. Moreover, the impact of a disruption would be significant.

Amazon illustrated the principle of investing in caution when it shut down its Kentucky facility for 48 hours of deep cleaning in March 2020 when three workers tested positive. While the company had earlier been hesitant to shut facilities, it eventually became proactive by overestimating the risk.

While estimating disruption probabilities is difficult, narrowing the range can significantly reduce total expected cost of misestimation. In their numerical study, Lim et al. (2013) quantify the benefit of narrowing the disruption probability range in a variant of the facility location model that accounts for fixed costs of hardening some of the facilities against disruptions to satisfy demand while the other facilities face random disruptions with probability q.

The authors assume that the set of true disruption probabilities is $q \in (\underline{q}, \bar{q})$ with $\underline{q} = \tilde{q}/(1+\delta)$ and $\bar{q} = \tilde{q}/(1-\delta)$ where $\tilde{q}$ is the median estimate and δ the estimation error rate. They compute the estimate $\hat{q}^*$ of the true disruption probability that minimizes $\tilde{F}(\cdot)$, the worst case cost of mis-estimation of disruption probability in the range $\{\underline{q}, \bar{q}\}$. Their results are reproduced in Figure 3 where r corresponds to the ratio of the cost of a hardened (not subject to disruption) facility to an unhardened facility, subject to disruptions with probability q.

Consider the case where $r = 2$, $\tilde{q} = 0.03$, and $\delta = 0.9$. The range of disruption probabilities in this case is $\underline{q} = 0.03/1.9 = 0.016$ to $\bar{q} = 0.03/0.1 = 0.3$. In this case we obtain $\hat{q}^* = 0.0846$, which is a more conservative estimate of the disruption probability compared to $\tilde{q} = 0.03$. In the range 0.016 to 0.3, using $\hat{q}^* = 0.0846$ as an estimate of disruption probability results in a maximum increase in expected total cost (relative to the true disruption probability) of 2.31% compared to an increase of 10.21% if $\tilde{q} = 0.03$ is used as an estimate. Clearly, a more conservative estimate limits the downside of misestimation. Also, the numerical example shows the value of bounding the true value of disruption probability within a range. In this case, if the range of disruption probability can be limited to be between 0.016 and 0.3, the cost of misestimation can be limited to 2.31%.

How commons lower the cost of investing in caution. The presence of suitable commons can be especially helpful in lowering the cost of investing in over-estimation on the side of caution. In an industrial setting, such a commons becomes more likely as flexible technologies become more prevalent and cheaper as discussed in earlier examples.

Investment in and use of data science, big data, and AI/ML can help narrow the range of estimates of the probability of disruptions, which, as we noted above, can more accurately optimize the investment in resilience. Industry commons making such technologies widely available can enable small firms to access these tools and reduce their range of disruption risk estimates. Companies like Amazon Web Services providing cloud services — already an example of a commons — already store data for firms and could offer a commons with such tools that would be especially beneficial to small firms.

5. Investing in risk mitigation inventory or reserve capacity

Investing in *risk mitigation inventory* (RMI) or reserve capacity for use in the event of a disruption can help increase resilience. Pharmaceutical companies typically carry a reserve of RMI of active ingredients for many of their drugs. *Reserve capacity* is excess capacity contracted to supply in the event of a disruption, with the contract requiring an upfront fixed cost and a variable (unit) cost incurred for the units supplied during the disruption. The delivery contracts signed by the US government with many pharmaceutical companies developing COVID vaccines are an example of reserve capacity. The government provided up front funds to ensure a supply of vaccine far in excess of the need for the entire population to mitigate against the disruption risk of some of the vaccines not getting FDA approval.

Modeling RMI and reserve capacity. For pharmaceutical supply chains, the question is where to hold inventory or RMI: upstream as cheaper raw material or downstream as more expensive finished goods. When dealing with normal demand uncertainty in supply chains, it is often optimal to hold inventory upstream given the lower holding cost upstream. However, in the presence of disruptions, it often helps to hold sufficient RMI in downstream local markets to protect against disruptions despite the higher cost of holding RMI downstream (Lücker et al. forthcoming).

Extending the above to distribution networks with one central location and several downstream distribution points, it is typically optimal, when dealing with normal demand variations, to pool inventory upstream to send it to the particular downstream location(s) where demand is higher than anticipated. However, when there is the risk of a major disruption, Schmitt et al. (2015) show that it often helps to decentralize the RMI downstream to protect against disruptions. While potential disruptions in decentralized locations are more frequent (due to the large number of decentralized locations relative to the one centralized location) than in the centralized locations, they are less severe because only sales in the local market are affected by the disruption, provided that the disruptions are not perfectly positively correlated. In contrast, disruptions at the single centralized location might have a more severe impact as all global sales are affected by the disruption. Fattahi and Govindan (2020) provide a general model that includes disruption risk and demand uncertainty simultaneously.

Tomlin (2006) studies a model where a firm can source from a reliable supplier with reserve capacity and a cheaper but less reliable supplier. He shows that reserve capacity is preferred over RMI as a risk mitigation strategy if disruptions are rare but long, whereas RMI is preferred if disruptions are frequent but short. In a similar setting, Chopra et al. (2007) explore how to best use reserve capacity to deal with disruption risk and recurrent risk (demand uncertainty). Dong and Tomlin (2012) study the interplay between reserve capacity and business insurances. The authors find that sometimes insurance policies and reserve capacity behave as complements (compare also Dong et al. (2018) for a similar analysis in a two-stage setting). In all these papers, reserve capacity can be considered as a real option, and can be valued as such.

How commons lower the cost of investing in reserve capacity and RMI. Given the high cost of excess capacity, a reserve capacity commons can significantly lower the cost of reserve capacity to a company. While no single health care provider can afford to invest in ventilator RMI or reserve capacity to produce ventilators, the government could significantly improve resilience by signing reserve capacity contracts with firms such as Ford and GM as discussed earlier. The government would pay an annual "premium" to reserve a certain amount of capacity to produce ventilators quickly in the event of a pandemic. This government sponsored commons would allow health care providers to access ventilator production capacity in the event of a pandemic.

Commons can also help lower the cost of RMI by virtually pooling inventory. An excellent example is provided by what Nordstrom, which has over 15 stores in its Los Angeles market, did during COVID. The company could have chosen to fulfill online orders from a centralized warehouse. Instead, Nordstrom chose to carry most of its inventory at its stores where the inventory carried was targeted to local preferences. The retailer created transportation capacity to allow product to be moved between stores for pickup. This virtual pooling of inventory allowed customers to place orders for products to be picked up at any of the Los Angeles stores, thus increasing the reach of the total inventory. Doing so also provided Nordstrom with resilience when faced with any local lockdowns, which typically shut one store, because customers could be served from the remaining stores. The short term challenge for the company was the cost of creating a transportation network to enable the movement of product between stores. However, if a third party were to offer an industry commons for transportation of goods in the greater Los Angeles area, it would be helpful not only to Nordstrom but also to other retailers in the region.

CREATING COMMONS

Having discussed the value of commons in the previous sections, we now discuss factors that facilitate the creation of a commons. We group these factors in three categories: technology-, demand-, and supply-driven factors.

Technology facilitating the creation of commons

Advances in information technology and flexible production technology can help facilitate the creation of industry commons. For example, information technologies such as augmented reality offer customers the opportunity to experience a product without being in its physical presence. Creating an information commons would be particularly attractive for small retailers who could attract geographically dispersed customers to be served using the fulfillment commons. Flexible production technologies such as 3D printing could be used to build commons that serve the most unpredictable part of demand across a variety of sectors. Building such a commons can improve efficiency by pooling the most uncertain portion of demand across multiple players and products. Simultaneously, such a commons improves industry wide resilience by easily facilitating tailored sourcing. Below are some examples of how technology is being used to create commons.

Using information technology to efficiently access financing from an existing commons. A Chinese fintech startup, JDH, uses mobile technology and blockchain to allow lenders to efficiently finance suppliers several tiers deep in electronics manufacturing supply chains. Fintech lenders such as Ant Financial (formerly Alipay, affiliated with Alibaba) and Kabbage (a US-based online financial technology company) can approve business loans within minutes by using AI. Increasing the lending frequency with smaller amounts and shorter delays enables lenders to reduce risk while better serving supply chain partners with just-in-time lending (Tang and Yang 2020). In this case technology allowed lower tier suppliers to efficiently access funds from an existing commons in the form of lenders. These funds are particularly helpful for small companies under extreme sales disruptions.

Using information technology to match flexible production capacity with demand from competing firms. Li & Fung, based in Hong Kong, owns no clothing factories or fabric mills. Their primary asset is a network of 15,000 suppliers in over 60 countries and an information system that identifies the location and capability of each supplier.[4] Most of these suppliers have production capacity that

[4] Linking Factory to the Malls, Middleman Pushes Low Cost. *New York Times*, August 7, 2013

is flexible enough to be used across competing fashion brands. Li & Fung commits to a certain amount of this flexible capacity from each supplier. The committed capacity and information system allows Li & Fung to create a supply commons for competing fashion companies. When a fashion company requires production capacity on short notice due to a sudden increase in demand, it can rely on Li & Fung to match its demand with the most appropriate supplier in terms of capability and total cost including duties. The commons created by Li & Fung aggregates demand fluctuation across competing firms, thus reducing the cost of serving a demand surge for a specific company. Even though Li & Fung charges a premium for the use of its commons, the price paid by any company is much less than what it would cost to commit to costly internal capacity to deal with a surge. Besides efficiently dealing with normal demand variation across competing brands, such a commons provides these brands with resilience under extreme conditions when supply from traditional sources is not guaranteed.

Using information technology to match taxi capacity with demand. Prior to Uber, taxi capacity and demand could not easily be matched unless they were geographically collocated. Uber has used its IT platform to create a commons for taxi capacity and customer demand where this matching can be done efficiently in real time. The Uber commons has also proved much more resilient during COVID compared to traditional taxi companies, even in places like Manhattan.

Using flexible warehousing technology and information technology to create a commons. Flexe provides on demand warehousing with over a thousand connected warehouses and allows companies to use its capacity and services on demand for short duration. The key to building this capability is flexible warehousing technology that allows warehouse storage to easily be reconfigured and information technology that allows item locations to be remembered for easy retrieval. As a result, Flexe warehouses behave as a commons that efficiently aggregates short term demand across a variety of companies. With the growth of flexible production technologies in many industries (for example shoes), third parties are likely to invest in creating more such commons that can aggregate demand across competing firms (which is often negatively correlated).

Supply-factors facilitating the creation of commons

We identify the following supply-driven factors that facilitate the creation of commons:

1. *Cost of flexibility*: As the cost of flexibility decreases, the value from the creation of commons in supply chains increases and the commons become more localized. A classic example is the transformation of the paint industry over the last two decades. Until the 1990s, paint was sold in cans of individual colors. This forced stores to carry a lot of inventory while often experiencing a significant mismatch of supply and demand. The high cost of color sensing and mixing equipment required large mixers in centralized paint factories. As technology allowing color sensing and mixing became cheaper, small-scale mixers were positioned in local stores selling paint. Each store carried one mixer that served as a commons across competing brands and all their colors sold at the store. The creation of this local commons made the supply chain much more efficient despite the proliferation in colors offered. Simultaneously, the creation and localization of the commons also made the paint supply chain much more resilient to disruptions.

2. *Scale and number of competitors*: An across-company commons provides greater value when there are many small competitors using the commons. A large player often has sufficient scale to create an in-company commons. For example, Amazon has sufficient scale to use backup facilities in its network to meet customer demand if the closest facility happens to be out of stock. Similarly, its scale is large enough that it has internalized the shared middle mile transportation commons across all its facilities. The internal commons improves efficiency for Amazon while also increasing resilience. For small retailers, who cannot afford such an investment on their own, the information and distribution commons provided by firms such as Amazon, Alibaba, Shopify, UPS, and Federal Express add a lot of value. This win-win situation leads to the creation of competing private commons vying for business from the small retailer without any government intervention.

3. *Correlation of the impact of a disruption across users of the commons*: Creating a commons adds much more resilience at lower cost when the impact of a disruption is not positively correlated across users of the commons. Such commons are more likely to be created by private parties

because the marginal value created by any capacity investment is higher in the absence of positive correlation. For example, third party logistics providers were effective during COVID because they could easily shift resources from industry sectors such as department stores that were shut down to supermarkets that saw a surge in demand. A commons capable of serving only supermarkets or only department stores would not have been as resilient because the impact of COVID within sectors was positively correlated with all supermarkets seeing an increase in demand and all department stores shutting down. In correlated settings, resilience can often only be provided by a government sponsored commons. For example, the strategic petroleum reserve had to be created by the government because the impact of an oil embargo is positively correlated across all refiners. No private party could justify the cost of building resilience in such a setting.

4. *Cost of aggregating available supply into a commons*: In many instances of disruption, there is plenty of supply available but the available supply cannot easily be matched with demand. In such a situation, reducing the cost of creating such a match makes it much cheaper and easier to create a commons. A lot of fintech efforts such as the one by JDH mentioned earlier are using technology to match available funds at lenders with potential borrowers who could not be accessed profitably without technology. By reducing the cost of access, technology facilitates the creation of a virtual commons that is simultaneously more efficient and more resilient.

Demand-factors facilitating the creation of commons

We identify the following demand-driven factors that facilitate the creation of commons:

1. *Demand uncertainty*: As demand uncertainty increases, the value of creating a commons increases, often resulting in private commons that aggregate high uncertainty demand. Paint mixers at paint stores serve as a commons that are shared across competing manufacturers and colors. The installation of these mixers at paint stores was accompanied by a proliferation in color availability because the mixer commons adds the most value when demand for each color and manufacturer is hard to forecast. When demand uncertainty is low, however, it is challenging to develop a commons because it provides little value in the face of normal variability. The crude oil supply chain offers

an example. Normal variability in demand for crude is not large enough for most companies to carry large amounts of crude in inventory. While this functions well during normal times, it creates significant problems during a supply disruption such as the 1973-74 oil embargo. To improve resilience, government intervention was critical to creating a commons in the form of a strategic petroleum reserve. This was not an investment any single company could afford to make.

2. *Demand correlation across the users of the commons*: Creating a commons adds much more value when demand is negatively correlated across users of the commons. The paint example is a perfect illustration of this principle. Total demand for paint at each store is relatively predictable and is divided among competitors. Thus, demand across competitors will be negatively correlated because an increase in demand for one manufacturer must come at the expense of another. The store mixer (the commons) that is shared across competitors thus becomes even more valuable because its utilization stays relatively stable independent of which competitor is winning.

3. *Demand for product variety*: As demand for product variety (including personalized products) increases, the existence of a flexible commons that can produce all products becomes more valuable. The increase in variety makes it harder to forecast demand for each product, thus increasing the value of a flexible commons that only requires an aggregate forecast.

RESEARCH OPPORTUNITIES

In Table 2 we list a variety of questions that need to be answered to create, maintain, and use an industry commons. These questions relate to the structure of the commons, the pricing of the commons, the optimal use of the commons, the role of government, the impact of the commons on industry structure and the role of product proliferation in the presence of commons.

Commons and modeling opportunities

Answering these research questions requires modeling disruptions along multiple dimensions and the actions of multiple parties (such as the firm, the government, and competitors) engaged with the commons. New models have the opportunity to capture the dynamics associated with the spread of a disruption across a global supply chain and similarly with its recovery. Ivanov and Dolgui (2020)

No.	Research question
1	What is the comparative advantage of third parties like Shopify and UPS versus existing large platforms like Amazon in creating an information and fulfillment industry commons?
2	Is there a role for "best of breed" industry commons that only focus on a part of the order taking and fulfillment process such as warehousing?
3	How should small and large firms use the industry commons?
4	How should the owners of industry commons price their services? When does pricing based on use make sense? When does subscription pricing make sense?
5	Can markets be created to trade capacity that has been reserved on a flexible industry commons?
6	When should the capacity of the commons be centralized? When can it be localized?
7	How might the creation of a commons impact industry structure?
8	When does the existence of industry commons encourage firms to produce locally rather than off-shore?
9	When does it make sense for the government to invest in or offer incentives to create an industry commons?
10	How should the government create future commons for urgently needed products – whether medically critical items such as vaccines or PPE – that cannot be anticipated at the moment as regards quantity or form?

Table 2 Research questions related to the creation and use of industry-commons

review the quantitative literature on 'ripples' of disruption and list research opportunities based on the WHO's five stages of response to a pandemic. Large multi-commodity network flow problems over many time periods could be expanded for shocks and disruption. In the context of electricity networks, Strbac et al. (2016) provide an overview of the modeling approaches for assessing the risk of operation of transmission and distribution networks.

Modeling pandemics requires a more careful consideration of the uncertainty source. It is important to differentiate between the fundamental uncertainty source (i.e. the true cause of the uncertainty such as labor shortage) and secondary effects (such as supply shortages or shifts in demand). Modeling the fundamental uncertainty source can be helpful when considering how the different uncertainty parameters interact with each other and how they are aggregated as supply or demand disruptions. We believe that techniques such as robust optimization may be helpful in modelling such fundamental uncertainty sources given their successful applications in various areas (Ben-Tal et al. 2009).

The role of government as an actor in supply chains has been studied mostly in the context of subsidies (Wang et al. 2019), sustainability (Chen et al. 2019), or reverse supply chains (Heydari et al. 2017). Such work needs to be expanded for government-initiated or funded commons. Companies and other competing organizations have to cooperate or compete, an issue that appears even in fashion supply chains as in case study of competing companies (Rafi-Ul-Shan et al. 2020) and even in humanitarian supply chains with multiple NGOs (Fathalikhani et al. 2020). Given the multiple correlated dimensions of supply chain risk – extreme or not – it is also worthwhile considering copulas or multivariate probability distributions (Clemen and Reilly 1999). Finally, knowing that people do not always react rationally to a disruption – we need to include behavioral responses in our models (Sarafan et al. 2019). Table 3 summarizes these modeling opportunities.

COVID-19 has provided us with a live study to expand and update our understanding of supply chain disruption and strategies for building resilience. We have offered a framework for thinking about these issues around the notions of commons at different levels, and the lower cost of resilience resulting from the commons. We hope that such framing will initiate more research and ideas into the creation of commons and their use in increasing resilience at low cost.

No.	Modeling opportunity
1	Time-phased or latency modeling
2	Shock transmission over time or ripple effects
3	Large-scale models across companies
4	Robust optimization on the fundamental uncertainty set
5	Including the government or public sector entity in the supply chain
6	Models of cooperation, competition, and coopetition
7	Multivariate probability distributions or copulas to capture 'correlation' risk
8	Reactions to risk based on behavioral findings

Table 3 Modeling opportunities for research in extreme supply chain conditions created by COVID-19 and responses, including the use of industry commons.

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