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Paradoxes and mysteries in virus-infected supply chains: Hidden bottlenecks, changing consumer behaviors, and other non-usual suspects

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Abstract In the early onset of the COVID-19 pandemic in the U.S., consumers experienced surprising shortages of essential goods that appeared to be unrelated to the pandemic: toilet paper, yeast and flour, and meat cuts. The usual explanations—attributing these shortages to demand spikes—often failed to provide an adequate explanation or predicted only temporary shortages. But these shortages ended up being real supply-chain struggles for which the true causes revealed a deeper set of unusual causes. Our detailed analysis of these supply chains identifies overlooked failure factors and hidden causes. We conclude with the profound lessons learned from the pandemic crisis on supply chains and the implied challenges of building resilient supply chains for the future, which require rethinking the relevant systems we plan and optimize. The level of investment required for building firm-specific redundancy of assets and operational flexibility might be prohibitive for any one firm, or their financial stakeholders, to pursue and accept.

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1. Why was it so hard to buy toilet paper?

Starting in late February 2020, the U.S. struggled to contain the spread of the COVID-19 virus. At the same time, in the early months of the pandemic, from March through late June 2020, U.S. consumers frequently saw grocery store shelves empty of essentials like toilet paper, disinfectant wipes, yeast and flour, and their favorite cuts of pork and beef. The supply chains for these products struggled to adapt to the demand and supply shocks of this virus-infected environment, leading to significant shortages, some temporary (e.g., toilet paper) and others prolonged (e.g., disinfectant wipes, certain meat cuts).
Almost every day from March 2020 onward, there were newspaper stories or blog posts about product shortages (e.g., Cagle, 2020; Oremus, 2020). Behind each such story was an underlying exasperation over the good shortages, which seemed to the untrained eye unexplained and irrational. The usual generic explanations offered in such stories of outsourced supply chains—unpredictable demand, foreign suppliers, and erratic tariffs—failed to explain the magnitude and duration of the observed shortages. In many cases, the shortages were a symptom of deeper supply chain struggles. As supply chain experts, we can understand shortages and supply chain struggles only when we fully account for the differentiating characteristics in product markets and supply decisions. A detailed supply chain analysis of the pandemic-induced shortages of the above-mentioned essential goods reveals that, even though shortage was the same observed outcome in all cases, the true causes—and the relative importance of factors behind them—were very different. Some of the causes were either new, underemphasized, or completely ignored.

We delved into the details behind the supply chain of each essential good that experienced unexplained shortages during the pandemic. Then, we identified both the usual causes (i.e., factors easily identified as such, often based on observations from previous risk events) and unusual causes (i.e., revealed in a significant way to be the real causes through this pandemic crisis, and often profound) behind the shortages. Table 1A summarizes usual causes and Table 1B the unusual causes across the analyzed industries. Using this understanding, we make suggestions for building and managing resilient supply chains for future crises.

Table 1A. Usual causes for short-term shortages

| Usual                                | Yeast & flour | Toilet paper | Disinfectants | Meat |
|--------------------------------------|---------------|--------------|----------------|------|
| Demand increases                     |               |              |                |      |
| Irrational ordering & hoarding       |               |              |                |      |
| Unpredictable demand                 |               |              |                |      |
| Factory closures                     |               |              |                |      |
| Imported from China                  |               |              |                |      |
| Lean supply chains                   |               |              |                |      |
| Tariffs                              |               |              |                |      |
| Regulatory restrictions              |               |              |                |      |

Table 1B. Real causes of pandemic-induced supply chain struggles

| Real                                  | Yeast & flour | Toilet paper | Disinfectants | Meat |
|---------------------------------------|---------------|--------------|----------------|------|
| Demand shift among segments           |               |              |                |      |
| Changing consumer behavior            |               |              |                |      |
| Hidden manufacturing bottlenecks      | Yeast (not flour) |          |                |      |
| Logistics bottlenecks                 |               |              |                |      |
| Inflexibility of focused production   |               |              |                |      |
| Shortages of packaging material       |               |              |                |      |
| Raw material shortages                |               |              |                |      |
| Corporate procurement hoarding        |               |              |                |      |
| Skilled labor unavailability          |               |              |                |      |
| Changing supplier priorities          |               |              |                |      |
| Industry structure                     |               |              |                |      |
| Costly switching & future investment  |               |              |                |      |
2. Shortages in yeast and flour

2.1. Hidden bottlenecks in flour chains

In late March 2020, with severe lockdowns across the U.S. and with many people in work-from-home (WFH) mode, many of us turned to baking as a comfort activity and to prepare more meals at home. The demand for flour had increased at least three times higher than usual by the third week in March, and the yeast sales were up over 600% relative to a comparable week in 2019 (Mak, 2020). Grocery store shelves were empty and supply chains were trying to catch up.

While bottled water, rice, beans, and dried pasta are common missing items in grocery stores after weather-induced risk events (e.g., hurricanes, earthquakes, tornadoes), yeast and flour missing from the shelf has been rare in the last 50 years. What made it even more curious was that the flour was missing from grocery stores and supermarkets that had an abundance of packaged bread and flour-based processed foods. We need to temper the immediate explanation of drastic demand due to irrational ordering and hoarding behavior by consumers with the fact that the demand for food services was mostly shut down due to the severe lockdown. Demand at an aggregate level for wheat flour had not increased.

To uncover the real causes of the flour shortage, we need to understand the overall flour supply chain and its customer behavior in detail. A rough-cut map of the flour supply chain appears in Figure 1.

The market has two distinct segments: consumer retail and food services (see Fig. 2). While the retail market is interested in 5- and 10-pound bags, the food services customers receive bulk orders of 25- to 50-pound bags. As the food services demand declined, the demand for retail size bags of 5 pounds skyrocketed at almost three times the normal level (Cagle, 2020). In addition, that increase was happening in March, a typically low retail demand month for flour, which has a predictable seasonal pattern that peaks in November-December.

At the back end, row crops such as wheat and corn were in abundance as inputs to the flour mills. With the U.S. growing over 120 billion pounds of wheat and less than 2% of it going into retail flour (Dunn, 2020), the increase in retail demand could be easily supported by the wheat supply. At the next stage of the supply chain, the main flour manufacturers handle the milling and packaging process through a network of their own mills, partner mills, and packaging facilities. The traditional bottleneck (i.e., the throughput constraining process) is the milling process, and sometimes a hidden bottleneck is the packaging. For efficiency reasons, these facilities focus their capacity on supporting one market segment, with the majority dedicated to food services. For example, King Arthur, one of the largest flour companies, has only seven out of the 45 mills handling the smaller size packaging in support of retail groceries (Dunn, 2020).

Increasing bottleneck capacity through extra shifts was an immediate lever to pull, especially for automated processes like milling and packaging. However, the involved labor is highly skilled, and its availability became the next constraint. Another hidden bottleneck that hindered the effort to rebalance the distribution needs between the market segments was the available transportation capacity. The preplanned efficient, low-lead-time bulk and large bag shipments of flour using train and full truckloads to a few large national warehouses had been replaced with smaller size, shorter lead-time shipments to many grocery stores and local warehouses.

In summary, the usual suspects’ explanation of strong increases in flour demand, which was countercyclical and accentuated by the hoarding behaviors of inexperienced bakers, was effective in explaining the early flour shortages. However, they failed to explain the prolonged duration of these shortages especially when the aggregate flour demand, due to the drastic decrease of food services demand, slowed down. The keys to the

Figure 1. Supply chain of flour

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Farms —> Flour Mills —> Packaging —> Bakeries —> Retailers
|                        | “Usual Bottleneck” | “Hidden Bottleneck” |
|------------------------|-------------------|---------------------|
| Farms                  |                   |                     |
| Flour Mills            |                   |                     |
| Packaging              |                   |                     |
| Other Food Mfg.        |                   |                     |
| Food Services          |                   |                     |
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mystery of the flour supply chain, what we refer to as the unusual suspects, were:

- Unexpected demand shift between market segments, with a revealed inflexibility at the packaging lines to handle such a shift;
- Skilled labor unavailability, a constraint to temporary capacity expansion of automated facilities; and
- Logistics bottlenecks, in this case mostly trucking capacity, that failed to accommodate shifting requirements because of the demand shift.

By early July 2020, flour shortages had mostly disappeared. Retail consumers started to accept 10-pound bags from Amazon and Costco, with the necessity becoming a virtue in a newly exhibited buy-and-share-with-neighbors/friends behavior. Still, demand uncertainty will remain in the industry for the next 2–3 years. How fast will the food services demand return in the expected gradual return to schools, universities, restaurants, sports venues, and hotels? Is this newfound love for baking a lasting consumer behavior—and if so, at what level—or will it evaporate as bakeries and restaurants serve our needs for bread and pastries? If both food services demand comes back quickly and the retail demand stays strong, then we should be getting ready for another round of flour shortages.

### 2.2. Longer lead time processes and the yeast supply chain

The yeast supply chain, depicted in Figure 2A, exhibits similarities to the flour chain. An exploding level of demand hit the front end, with increases quoted at the level of 600% in March 2020 (Mak, 2020). Similar to flour, the market has retail (grocery stores, supermarkets, etc.) and food services (restaurants, bakeries, etc.) segments. Grocery stores and supermarkets buy dry yeast due to the lower life cycle and ease of storage. Food services like bakeries, in particular, prefer fresh yeast. The observed shortages in the yeast chain are for dry yeast.

The back end of the chain relies on a longer lead time batch manufacturing process (see Figure 2B). It starts with a batch of diluted molasses and seeds with the desirable strain of yeast. Then the batch goes through a fermentation process in giant vats. ABI Mauri, a St. Louis-based manufacturer of the popular Fleischman’s Yeast brand, had 10–14 days of production lead time, which is hard to further compress due to product quality concerns (Mak, 2020). After fermentation, the product is centrifuged, aerated, filtered, dried, and packaged.

Manufacturers ship large bags (around 800 kilograms) to their packaging partners that will
produce the small bags or jars (7–10 grams) of dry yeast that home bakers buy. From there, the product is distributed to grocery stores and supermarkets.

As the dry yeast chain was exposed to the large demand increase, the sourcing of molasses and the growing process had adequate capacity to handle it. Once again, the packaging process became the bottleneck. In a well-streamlined, predictable demand process (seasonal with a peak in November–December), the packaging process runs at high levels of utilization, and some of its packaging materials are sourced from overseas. There is little space for temporary capacity expansion through extra shifts, and often the lack of packaging material is a serious constraint to the output.

Yeast shortages persisted through early summer 2020, with enterprising sellers cutting bulk packets of yeast into smaller bags and selling them online at exorbitant prices. Many home bakers explored the do-it-yourself (DIY) options of growing yeast by placing old flour, water, and dried fruit in a jar (i.e., sourdough starter), and then allowing a fermentation process of 24-48 hours. Again, the usual suspects’ explanation of unexpected demand failed to explain the prolonged duration of such shortages for 3–4 months into the summer of 2020. In a manufacturing process with no molasses (input) shortages, and no fermentation vat constraints, the long-lasting shortage causes have to be looked at beyond the usual ones. The unusual causes for this case are:

- The drastic demand shift from fresh to dry yeast, and serving the needs of a more dispersed, smaller packaging size retail market versus a more concentrated, larger order food services market;

- Shortages of packaging material in support for the increased demand segment; and

- The lead times of the fermentation process (2 weeks) in combination with a packaging distribution time of another 2–3 weeks ended up being a factor.

Again, we see the need to balance the focused efficiency of streamlined flows by market segment and the need for processing and distribution flexibility that can accommodate demand shifts among segments. Shortages in yeast and flour lasted and will continue to last for longer than the usual suspects predict.

3. The missing toilet paper: Surprising shortages

While March was characterized by shortages in many essential items, it was the toilet paper that was the most surprising. Toilet paper is a highly predictable usage, low value-to-weight, bulky-to-store item that is served by well-oiled, cost-efficient regional supply chains. A record 70% of U.S. grocery stores, including online sellers, ran out of toilet paper, and toilet paper hit a record sales increase of 734% on March 12 as compared with the same day a year ago (Wieczner, 2020). How could we be running out of toilet paper when its overall usage was not affected by the pandemic crisis?

The early explanations for the toilet paper shortages oversubscribed to the irrational orders and hoarding behavior of consumers, which were causes that would explain temporary demand spikes. However, a deeper analysis of the underlying supply chain (see Figure 3) will allow us to uncover other causes that ended up playing a significant role in this event.

Here is the list of causes from the usual suspects for the toilet paper shortage:

- Unpredictable demand for toilet paper after the lockdown in the pandemic crisis. COVID-19 infections do not increase toilet paper usage by much, but where the toilet paper is used shifts heavily from the workplace and entertainment

Figure 3. Toilet paper supply chain
venues to homes, with an estimate of around 40% increased home usage (Oremus, 2020).

- Hoarding behavior is the obvious next explanation for the unexplained level of demand peaks for toilet paper in mid-March.

- Lack of manufacturing capacity is the immediate next reason for the prolonged failure of the supply chain to respond to the temporary demand spike. There are 83 million rolls of toilet paper produced per day in the U.S. within a chain utilized at around a 90% level, with another 4 weeks of inventory within the distribution system (Wieczner, 2020). Quick calculations argue that available capacity and inventory can withstand a 30%–40% demand increase over 2 weeks. However, it will not absorb a prolonged and heavily inflated increase over a few weeks.

- Factory closures were not an issue at all for the toilet paper industry given its highly automated manufacturing process.

- Imported from China rationale is not applicable here. Low margins of a predictable high-volume demand product, with a low value-to-weight ratio that is bulky to store, argue for efficient local chains with short pipelines and low levels of inventory within the chain. The toilet paper supply chain for the U.S. market is a U.S.-based one.

- Raw material inputs are the next suspect on the list. However, softwood and hardwood trees are not in short supply, with pulp coming from far away, mostly Brazil. The predictable long lead time chain carries at least 6–8 months of inventory close to production sites. There were no raw material shortages even for the level of demand increases seen in mid-March.

Delving deeper into the toilet paper supply chain details (see Figure 3), we again have a market segmented into commercial customers using larger industrial-size rolls (used in airports, stadiums, office buildings, etc.) and the consumer segment of homebuyers consuming higher quality, multiple-ply, smaller size rolls. Commercial rolls made out of recycled fiber are shipped in large pallets, while the consumer ones made out of virgin fiber are shipped in branded packs of 6–12 rolls. As before, there is a shifting of demand from the commercial to the consumer segment. It is interesting to note that while our grocery store shelves were empty of toilet paper rolls, our schools, cafeterias, dining spaces, and entertainment venues had lots of toilet paper.

Again, the pandemic exposed the inflexibility of the segment-focused efficient packaging lines and distribution systems to changing product mix in demand shifts. The main manufacturers (e.g., Procter & Gamble, Kimberly Clark, Georgia Pacific) were willing to reduce the offered product line variety. The variety reduction allows larger batch production and increases output. However, the manufacturers were not willing to reallocate capacity by repurposing their commercial-focused packaging lines. The commercial business had better margins, higher volume, and increased efficiency, and they expected it to come back soon.

The shift in segment demand, as we have seen before, translated subsequently into logistical constraints, mostly in trucking capacity. Trucking capacity is a resource shared across many of the struggling supply chains, and the demand shifts across segments, as well as the need for a quick response to demand spikes, stretch its limits, and make it an oft-ignored hidden bottleneck.

In summary, while the early hoarding behavior of WFH consumers drove the demand spikes on small-roll toilet paper, the prolonged duration of the retailer shortages was due to hidden bottlenecks in the supply chain. These were the inflexibilities of packaging lines to adapt to the demand shift, efficiently segment-focused manufacturing and distribution operations, decision inertia in capacity reallocation between segments, and a rationing game in the constrained retailer/online sellers segment.

4. Imported raw materials and disinfectant shortages

The reported demand increase for spray disinfectants and wipes in early March 2020 was about 500% over the same time a year ago (George-Parkin, 2020). It soon led to serious shortages that lasted through the fall. While the early stories on sanitizers and wipes were explained with panic ordering and hoarding behavior, this is a story of a global supply chain with a long lead time, imported raw materials. Sanitizers are products that many companies can make on short notice, and we heard of perfume and cosmetics companies (e.g., LVMH), small-batch distilleries (e.g., Absolut Vodka), or even prison laborers in New York state producing them, but only if the needed specialty chemicals were available. That is exactly where the bottleneck in this chain is—with such raw materials sourced mostly from China—with long
lead times of 6–8 weeks. Furthermore, from January to mid-March, China needed such materials for its use in the middle of its virus crisis.

The study of the supply chain of these products (see Figure 4) reveals large institutional buyers on the market side (e.g., hospitals, retirement homes, essential factories), which were given priority over the retailers serving the stay-at-home consumers. Even Amazon, Walmart, and Costco experienced such shortages.

The manufacturers of these products (e.g., Reckitt Becksiner [Lysol], Clorox, Gojo [Purell]) see a stable market demand regularly, with some seasonality around the flu season, and run efficient, high-utilization, low-inventory chains in response. Their suppliers are specialty chemical manufacturers of quaternary ammonium compounds, or quats, with automated batch manufacturing facilities serving their customers on a short lead-time basis. The raw material chemicals are sourced mostly offshore, and mostly from China (e.g., ethanol, isopropyl alcohol, various chlorides for sanitizers, towelette fabric for wipes). The quats chemical producers (e.g., Lonza, Pilot Chemical, Stepan) typically carry an adequate raw material inventory of 2 months to protect the supply chain from the raw material lead times. The increased end-product demand was expected to reach a certain level in early January 2020, and with the associated supply slowdown of 2–3 weeks of the lunar New Year coming up in late January, the raw material supply chain was fully stocked when the February demand increases hit. However, the observed 500% increase quickly depleted this inventory, with the supply chain drying up in late February (Kang, 2021).

While everyone expected that the dramatic increase in demand would be effectively dealt with by activating capable capacity from other industries (e.g., distilleries, cosmetics) or expanding the portfolio of chemical companies (e.g., SC Johnson, Dow Chemical, Eastman), these projections underestimated the true bottleneck in the supply chain: the long-lead-time raw material sourced from China. Three extra factors contributed to making such sourcing even worse: Tariffs increased the sourcing expense, thus reducing the ordering from this source in anticipation of lowered tariffs later; Supplier priorities changed as Chinese suppliers were diverting their production to the urgent healthcare needs of their country; and expedited logistic were constrained as expedited orders via commercial plane air cargo was not an alternative due to the near shutdown of international travel. Whatever capacity remained was prohibitively expensive. The ocean freight was slower than usual due to reduced capacity (e.g., labor availability) of the Chinese ports at the peak of the pandemic.

The raw material bottleneck proved a severe one that persisted for a long period. When shipments arrived in the U.S., they were rationed mostly to healthcare and government-related entities, and then large retail outlets. The large retailers inflated orders, trying to hoard as much of the limited resource as possible. Some producers bet on demand outlasting the pandemic and added capacity (Kang, 2021). As the raw material from abroad arrived, and the expanded capacity came into place, the retailers ended up with high sanitizer wipe inventories and deep discounts and promotional giveaways came into effect to clear them in

Figure 4. Supply constraints for disinfectants
early 2021. We all observed a classic bullwhip effect within the chain, whereby demand or supply shocks drive exaggerated ordering up the supply chain, creating cycles of shortages and increased prices, followed by resource overinvestment ending in overcapacity, high inventories, and depressed prices (see Lee et al., 1997).

5. Struggling U.S. meat supply chain: Food shortages, depopulated animals, and devastated ranchers

In early May 2020, the shuttered meatpacking plants had created a serious bottleneck for all the meat flowing through them, from chicken to pork and beef. As consumers rushed to the supermarkets, they found a limited variety of packaged meats and had to pay higher prices for them. However, the real pain was felt at the back end of the supply chain. The meatpacking factory closures affected most farms and ranches where the animals were raised. As the meat processing capacity was reduced by 40%—50% in the middle of the chain, the birds, pigs, and cows could not be slaughtered at the appropriate time and the right weight, and for storage capacity and economic reasons had to be euthanized. While at the front end, we were paying $1.39 per pound of beef trimmings in early May, an eight-fold increase relative to the $0.25 of early April, the cattle ranches were losing $300 per cow at the slaughterhouse and the pork farmers lost $100 per carcass. It is estimated that the beef cattle industry lost $14 billion, and the hog producers lost $5 billion in 2020 (Bedford, 2020).

Our detailed study of the meat supply chain (see Figure 5) revealed weak points and structural faults that threaten not only its current but also its future resilience. At the front end, the output of meatpacking facilities is handled by distributors specializing either in the neatly packaged branded meats we find in our supermarkets (retail segment) or the larger pieces of meat delivered to food services (e.g., hotels, restaurants). Even with the 30%—40% capacity reduction at meatpacking facilities, it was not clear that food shortages would follow. Demand from food services had substantially decreased due to the lockdown, and WFH consumers were not consuming more meat. But the way meat was consumed and delivered had changed. The efficient processing, packaging, and distribution system of large meat portions, “cold trains,” and refrigerated warehouses was seeing a slowing in demand. The labor-intensive butchering into small cuts, carefully branded packaging, and frequent deliveries via a pull system to multi-location supermarket chains were all seeing a sizable increase. The firms owning the bottlenecked meat processing facilities now increasingly preferred the food services market to avoid time-consuming butchering steps, large variety, and logistical complexities. For the meat packers, reduced capacity and fears about long-run food services demand coming back, despite some increases in retail demand, resulted in decreased orders to the feed yards, which then led to lowered cattle prices.

An industrial meat supply chain structure, driven by economies of scale in processing and complemented with the logistics technology of the

Figure 5. Meat supply chains

- Pork (refrigerated) exports to China were still surging early May
- U.S. commercial stockpile of meat rather large in the spring
- Beef trimmings cost 254/lb. (April 1) and were up to $1.93/lb. in early May.
relished ownership among four major firms: JBS, Tyson, Smithfield, and Cargill. Furthermore, a rather central location of mostly Midwestern plants ended up efficiently supplying the whole country. The meatpackers relied on low-cost immigrant labor in tightly packed, fast-paced assembly lines to further keep costs under control. However, the big and centralized paradigm in a pandemic, in particular when their labor was infected at high rates, proved to be the Achilles’ heel of the supply chain. For the meat processors, keeping the plants open even at reduced capacity, and with government support (e.g., essential infrastructure designation), became an economic priority. Their next lever to pull was narrowing their product portfolio towards products at the higher margin-per-hour of capacity used, and that meant products used by food services (e.g., military, hospitals, prisons) and export markets were still in play. At the grocery stores in May 2020, you could still find meat, but it might have been of a higher quality, or in specialized packages, and it was located in the more upscale supermarkets and boutique butchers. The conventional meat cuts were heavily rationed at the supermarket chains. Even though prices for conventional cuts increased, they were not as steep as for the special cuts. Nevertheless, they were still proving affordable for recently furloughed and unemployed consumers.

In summary, the meat supply chain was broken by the pandemic, and the broken link was where we thought the strength of the chain lay. The big, centralized, labor-dependent core proved vulnerable to the pandemic, and the chain lacked the flexibility to adjust to the demand shift away from food services. The meat-based supply chains need resilience in future crises to avoid opening the door of opportunity for plant-based meat. Consumers started developing some taste for it, and the faux meat chains with highly automated facilities saw no capacity bottlenecks.

6. From lessons learned during the pandemic to supply chain resiliency solutions for the next crisis

The supply chain lessons learned from the pandemic as summarized in our previous discussion are profound and revealing in their importance. However, the actions needed in place to improve supply chain resilience for future crises go beyond the usual recipes and are not without challenges. While the current literature repeats the usual broad remedies for the resilience of redundancy and flexibility built one company and one supply chain at a time—pandemic related in Shi (2020), broader literature in Bradley (2014) and Tomlin (2014)—we identify resource constraints cutting across supply chains and industries as hidden bottlenecks incapacitating quick recovery across many industries. We need collaborative solutions and coordinated investments across corporations, and potentially across industries and regions, to address future systemic resource disruptions. The need to assume a broader system perspective—rather than that of just the firm or the supply chain—in dealing with these black swan events is a viewpoint that has been underemphasized by the literature, corporate boardrooms, policymakers, and governmental agencies.

Resilient supply chains of the future have to be able to deal effectively with demand shifts among market segments. However, how do we create that process flexibility for such drastic demand shifts when the efficiency of functional good markets will not justify investments for the redundancy in facilities and materials to accomplish it? Flexible automation that allows for product mix changes in a wide portfolio of products that differ substantially in size, attributes, and materials might be an answer. However, flexible automation is not easy to achieve, and can only be designed when the product portfolio is both well understood and rather narrow. It comes at the expense of significant setups, the need for highly trained operators that can calibrate such flexible equipment and requires expensive investment relative to the size of the market segment. The trained labor can be a limited resource that cuts across companies in a region. Other innovative solutions require rethinking the manufacturing processes to create modularity of processing tasks, with some of the process modules robust in efficiency across a wide portfolio of products and markets, and others performed only when necessary for the specific product. On the material input side, there is a need to put in place processes that can create from original inputs for a specific product substitute inputs for the other market’s product line. But that again may depend on the capabilities of the industry or regional supplier network, and the needed transportation and distribution resources, another set of shared resources across a broader system (industry, region, etc.). The postponement logic, so admirably applied across products in complex product lines (e.g., product platforms with common components and modules, and delay product differentiation closer to the actual market; Tomlin, 2014), needs to be repurposed for processes. It has to be designed as a process postponement capability
in anticipation of sudden demand shifts, with some of these capabilities executed by downstream partners (e.g., distributors, third-party logistics, storage operators).

Firms are part of larger industrial systems sharing resources in terms of transportation, distribution assets, and trained labor, and they have limited visibility and allocation control. For such shared resources, coordinated planning is needed, especially on how they will be allocated in the presence of crises. Scenario plans have to be coordinated into well-orchestrated exercises among multiple firms and sector representatives with a focus on revealing needed target capacities. Oftentimes, investment in such targets will be beyond any one firm’s ability to sustain. As a result, cost subsidization on the part of industrial associations and/or regional governments might be required to enable the use of strategic-level shared resources.

The creation of strictly regional supply chains with short lead-time supply links of all input materials often is not the solution, as the economics of material markets, processing volumes, and the specialized processing nature of some components may necessitate global sourcing at a few locations with the right access and labor costs. Global links, and potentially complex global processing chains with significant lead times, are a reality we need to plan for to mitigate risk in preparation for future crises. However, there is a need to establish protocols on how such valuable global resources will be allocated in crises in the presence of government agendas, trading frictions, and lack of visibility and coordinated capacity planning. The usual firm-specific supply chain, or even country-specific supply network, of an imported resource is not big enough of a system to be planned for and to mitigate risk for low-likelihood events. Governments need to stress test crucial supply chains for their economies and invest in the strategic stockpiling of a vast array of raw material resources, as the U.S. does for oil reserves and medicine (see Sheffi, 2015). Industry-wide professional organizations need to create supply networks not controlled by any country so they can be less vulnerable to politics and country-specific agendas in the interest of reprioritization of resources. However, such actions necessitate the creation of global professional organizations and alliances that will undergo scenario planning of black swan events. These entities would outline needed corporate member investments and enforce agreed-upon resource allocation protocols.

In most cases, supply chain risk management assumes market structures and industry supply chain architectures will remain the same as they currently are. However, in extreme crises, underlying market structures, ownership architecture of existing assets, and the high-level design and structure of the industrial supply chain have to be examined as well. The efficiency structures under stable market conditions may need to be challenged for their vulnerability to potential extreme future shocks of a black swan nature. The inertia of individual firms, especially ones that have strong control in rather oligopolistic markets, leads to a preference to return to the same old structure. Encouraging change to new market structures and supply network architectures might have to come from representatives of the broader system, which cares for the interests of end-consumers and unrepresented economic agents.

The pandemic crisis infested supply chains with shortages, but at the same time exposed common failure themes and overlooked causes. It became apparent that in building the resilient supply chain of the future, we have to go beyond redundancy, buffering, and narrow operational flexibility. There is a need for planning, orchestration, and investments for constraining resources at a broader system level such as the industrial sector, regional government, and potentially the global factor market, as well as engaging nongovernmental broad stakeholder interest agencies, to help facilitate needed change to create truly resilient supply chains.

References

Bedford, L. (2020, May 14). Bottlenecks in the supply chain will have lasting effect on producers. Successful Farming. Available at https://www.agriculture.com/news/livestock/three-producers-speak-out-about-the-effects-of-covid-19-on-their-operations

Bradley, J. R. (2014). An improved method for managing catastrophic supply chain disruptions. Business Horizons, 57(4), 483–495.

Cagle, T. (2020, May 18). Two months into the pandemic, why is it still so darn hard to find yeast and flour? Nautilus. Available at https://coronavirus.nautll.us/two-months-into-the-pandemic-why-is-it-still-so-darn-hard-to-find-yeast-and-flour

Dunn, E. G. (2020, June 17). When bakers demanded more flour, King Arthur went to the mills. Bloomberg Quint. Available at https://www.bloombergquint.com/businessweek/how-king-arthur-dealt-with-a-flour-shortage-during-the-pandemic

George-Parkin, H. (2020, March 17). How long will essentials like toilet paper be hard to get? It depends. Vox. Available at https://www.vox.com/the-goods/2020/3/17/21183911/coronavirus-household-supplies-toilet-paper-hand-sanitizer-face-masks-amazon

Kang, J. (2021, May 21). Retailers couldn’t stock hand sanitizer fast enough. Now they can’t give it away. The Wall Street
Paradoxes and mysteries in virus-infected supply chains

Lee, H. L., Padmanabhan, V., & Whang, J. (1997). The bullwhip effect in supply chains. *Sloan Management Review, 38*(3), 93–102.

Mak, A. (2020, April 15). The yeast supply chain can’t just activate itself. *Slate*. Available at https://slate.com/business/2020/04/yeast-shortage-supermarkets-coronavirus.html

Oremus, W. (2020, April 2). What everyone’s getting wrong about the toilet paper shortage. *Medium*. Available at https://marker.medium.com/what-everyones-getting-wrong-about-the-toilet-paper-shortage-c812e13586e0

Sheffi, Y. (2015). *The power of resilience: How the best companies manage the unexpected*. Boston, MA: MIT Press.

Shi, W. C. (2020). Global supply chains in a post-pandemic world. *Harvard Business Review, 98*(5), 82–89.

Tomlin, B. (2014). Managing supply-demand risk in global production: Creating cost-effective flexible networks. *Business Horizons, 57*(4), 509–519.

Wieczner, J. (2020, May 18). The case of the missing toilet paper: How the coronavirus exposed U.S. supply chain flaws. *Fortune*. Available at https://fortune.com/2020/05/18/toilet-paper-sales-surge-shortage-coronavirus-pandemic-supply-chain-cpg-panic-buying/