Supply Chain Resilience:
Restoring Business Operations After a Hurricane

Summary Report

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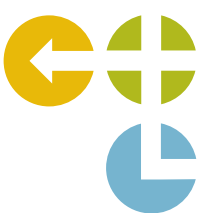

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Executive Summary

MIT's Humanitarian Response Lab at the Center for Transportation and Logistics (CTL) held a roundtable on supply chain resilience in the face of large-scale disasters. To gather a cross-sectional understanding of the issue, the event convened participants from academia, public sector, and private sector – who brought their respective perspectives to illuminate this crucial intersection of management science, government policy, and business strategy. To ensure candor, this report was prepared under the Chatham House Rule of not identifying the specific speakers or affiliations of the anecdotes, insights, or recommendations. The roundtable used three major hurricanes (Harvey, Irma, and Maria) during 2017 as a focal point for gathering multiple points of view from the public and private sector and spanning supply chains from manufacturer to retailer. The roundtable and this report are aimed to catalyze more systematic research of the issues and opportunities revealed by shared discussion of how business and government support survivors and restore a disaster-impacted economy.

The first half-day of the roundtable discussed supply chains for critical commodities following disasters – including water, food, fuel, and healthcare supplies – along with crosscutting issues regarding transportation. Participants described the surge in the demand and the impact of the storms on supply chain facilities, links, conveyances, workers, power, and more. Although each critical commodity and each storm was different, they shared many common phenomena. Overall, the storms impacted distribution more so than supply. Shortages of conveyances, congestion in the supply chain, and degraded infrastructure impaired the flow of aid and delayed the resumption of normal retail and business operations.

The second half-day took a more holistic look at how critical supply chains are managed in these kinds of crises and how they might be managed better in the future. Participants reported using a number of practices to support survivors and return to normal business operations. Both private and public organizations accumulated and relocated resources in anticipation of the hurricanes. Many organizations supported employees and their families to meet needs and enable return to work. Organizations used Emergency Operations Centers (EOCs) with tactical, operations-focused personnel to manage the crisis. Government agencies supported private recovery efforts through information and regulatory waivers in addition to direct aid to the survivors. Overall, companies sought to flex their networks to cover the surge in demand and serve the rest of the nation, too.

The discussions also revealed potential opportunities for improvement, especially in the realm of business-government coordination. For example, pre-crisis supply chain mapping and post-crisis visibility may enable better management of resources. In cases where detailed real-time data is impractical, aggregate indicators and sentinel data sources could provide timely, actionable insights. Better relationships among businesses and the many government agencies in all levels of jurisdictions could improve coordination in a crisis. Although the future of disasters may be dynamic and unbounded, research, development, and rehearsal of resilience strategies can help mitigate the black swans to come.

Introduction

MIT's Humanitarian Response Lab at the Center for Transportation and Logistics (CTL) organized this roundtable event to discuss supply chain resilience and capture fresh experiences and insights from the 2017 hurricane season that saw three major storms (Harvey, Irma, and Maria) strike the U.S. and its territories. The overall resilience challenge of these events was to support the survivors and restore normal business operations that provide both employment and goods to citizens of the affected areas. The handling of these specific events by public and private supply chains can help illustrate the event impacts, private-sector and public-sector solutions, and future opportunities for improvements by these organizations. Future research can further validate the observations made during 2017 and further refine strategies and tactics that public and private organizations can use to better manage critical supply chains in future disasters.

To gather a cross-sectional understanding of supply chain resilience in the face of large-scale events, the roundtable included three categories of participants -- academia, public sector, and private sector -- who brought respective perspectives on the management of disaster response and recovery. Representatives from MIT brought a research focus that included both supply chains and organizational resilience. Representatives from the federal government and a number of NGOs brought a public-sector point of view on the response to disasters which, in turn, rely on supply chains and logistics to deliver aid to survivors. Finally, representatives from the private sector included people from manufacturers, distributors, retailers, and carriers who had experience during these hurricanes with supply chains for critical materials such as water, food, healthcare, and fuel.

The meeting comprised two half-day sessions with an overnight for reflection. The first day discussed supply chains for critical commodities following disasters – including water, food, fuel, and healthcare supplies – along with crosscutting issues regarding transportation. These commodities were not meant to be exhaustive, but to elicit specific stories from different organizations about supply chains that play a key role in disaster response and recovery. The second day took a more holistic look at key facets of how critical supply chains are managed in these kinds of crises and how they might be managed better in the future. In particular, it looked at issues such as communications, coordination, supply chain network dependencies, data, analytics, and resilience strategies.

Each session began with short presentations by one or more participants followed by wide-ranging discussions. The aim was to gather multiple points of view from the public and private sector spanning supply chains from manufacturer to retailer. These presentations and discussions revealed a wide range of supply chain impacts, solutions, and future opportunities, which are described in the sections below. Interestingly, many of the stories revealed a set of common impact patterns in disasters and common solutions pursued by public and private supply chains. For example, all supply chains in each of the 2017 events faced limitations in transportation capacity. Although future research will, no doubt, delve into the variations associated with different disasters and different critical commodities, a common framework for supply chain resilience may underpin disasters of all types. By understanding the system-level interactions, this roundtable and future work can improve the lives of survivors and help return the affected economy to normal faster and more efficiently.

Impacts on Critical Supply Chains

A common issue mentioned during the roundtable was the lack of unused capacity in most U.S. supply chains. By and large, U.S. companies run highly optimized supply chains designed and managed to ensure a combination of low costs and high service levels (often measured by availability of goods on retail shelves). Many companies use lean practices that minimize waste by avoiding excess inventory, excess assets, excess labor, and so forth.

A second contextual observation was that national supply chains operate as networks of independent companies. Few companies own or directly control all the manufacturing, transportation, distribution, and retail assets required to extract and process raw materials into finished goods and deliver them to consumers. Each company typically manages some segment of the chain with a portfolio of suppliers, service providers, and customers. Transportation, especially, is often handled by third parties. To the extent that companies do not have continuous, uniform flows of freight in both directions among supply chain facilities, it's much more cost effective for them to rely on outside transportation companies who smooth the peaks and valleys in shipping volumes and directions of flow.

The overall result is a lean transportation sector with assets shared among various sectors of the economy at different times to handle the usual annual cycles in supply (e.g., agricultural production) and demand (e.g., selling seasons for summer weather, back-to-school needs, holiday gifts). The transportation industry, especially trucking, has become leaner over time. Since the 2008 recession, the number of trucks has declined by 15%, although total freight carried has remained constant.

It is within this context of highly optimized lean national supply chains that disasters such as hurricanes inject their chaos. During each event, public officials and private sector leaders attempt to manage the disaster. They bring needed supplies to the affected area and deal with the impacts of an interruption in the local or regional economy. These impacts can be divided into the six categories described below, aligned with the network structure of supply chains.

Impacts on Demand

Many critical commodities discussed during the roundtable saw surges in demand both before and after the storms made landfall. In Florida, before Irma made landfall, water sales surged 400%, fuel sales increased 300%, and battery sales ran as much as seven times their normal rate. These increases may have reflected some combination of rational pre-stocking, evacuation-related activity, or hoarding. In Puerto Rico, diesel sales surged 10X after Maria made landfall to power all the private generators, pumps, and other equipment used during the prolonged power outage on the island. Other product lines had unexpected changes in demand brought on by storm-induced factors, such as the addition of one million people to Florida's Supplemental Nutrition Assistance Program (SNAP) and the post-hurricane replenishment of perishable foods. Demand spikes were seen in many locations, especially following a late shift in the storm track for Irma from Florida's East Coast to its West Coast, which meant scarce supply even in areas with minimum impact from the storm.

In addition to surges, companies faced changes in demand patterns affecting both product mix and location. For example, home improvement chains began to stock larger amounts of bottled water that customers wanted to buy as they purchased construction supplies. Companies also expanded their distribution destinations to encompass orders and donations for shelters and charities. Healthcare product distributors and related service providers, especially, expanded distribution to non-traditional locations such as shelters.

Finally, following the initial storm-related demand surges came an unpredictable second wave of demand as consumers, retailers, and distributors restocked shelves of depleted inventories. Perishable products had particularly high post-storm demand because these inventories had been reduced to near zero. Restaurants and grocers had to replace nearly 100% of their fresh, refrigerated, and frozen foods. In other cases, such as bottled water, companies were having to reabsorb months' worth of product that they ordered in the heat of the moment but did not consume or sell.

Impacts on Network Nodes

Supply chains typically encompass a network of facilities that comprise the manufacturers, distributors, and retailers who transform raw materials into finished goods and provide them to consumers. These nodes can be susceptible to damage or impairment during a disaster. Overall, discussions about the 2017 hurricane season suggest that distribution and retail were hit more heavily than manufacturing.

Some companies did have some damage to manufacturing operations. For example, a key resin supplier to plastic water bottle manufacturing was damaged by Hurricane Harvey. All three hurricanes caused water-bottling plants in the affected areas to go down. Harvey damaged refineries in the Houston area, inducing a modest increase in gasoline prices across large sections of the United States. There were also some significant concerns about U.S. pharmaceutical supplies due to the high concentration of drug makers in Puerto Rico. Yet aside from some local outages, some price increases, and some fears, the storms did not cause serious sustained impacts on U.S. supplies of critical goods because companies found other supplies or managed to restart production before supplies ran out.

Companies also cited many examples of damage to supplier warehouses, company distribution centers, customer warehouses, and retail outlets. If either the origin of some goods or the destination of those goods was down, the goods couldn't move and the flow stopped. In many situations, companies reported that the facilities were largely intact but that a lack of other resources such as power, workers, trucks, or accessible roads prevented facility operations (see other sections about these impacts). Damage to port facilities such as cranes also affected the ability to distribute goods.

Impacts on Network Lanes

Supply chains depend on reliable, high-capacity networks of interconnecting lanes that include transport by road, rail, air, and sea. In the case of both Harvey and Irma, the hurricanes closed or congested major interstate highways. Companies were forced to either find more circuitous routes, waste driver-hours and fuel on slow-moving congested roads, or wait for the roads to improve.

The storms also damaged local roads critical to the "last mile" of a supply chain where products reach retail shelves and

consumers. Harvey flooded many roads in metropolitan Houston area. As one company noted, their Houston distribution center was not damaged but it was surrounded by a moat of water, impeding access. Hurricane Maria caused extensive damage to Puerto Rico's road network. This damage impacted the re-opening of retail outlets and the ability of consumers (and workers) to reach these outlets. In some cases, existing supply chain links were damaged in multiple ways with cascading effects. For example, the U.S. Virgin Islands (stuck by Irma) had strong supply chain links to Puerto Rico (struck by Irma and Maria), which had strong supply chain links to Florida (struck by Irma).

In addition to physical road damage and congestion, companies also described restrictions imposed by government-controlled access points and curfews. These restrictions also caused congestion and impairment to critical supply chain flows. For example, strict curfews worsened congestion and prevented restocking of retail stores during off-hours. Experience with this issue varied among the roundtable participants, with some companies reporting no problems with access. Some anecdotal evidence suggested that perimeter controls may have been more relaxed than in previous storms but other comments suggested that local authorities faced a shortage of resources that prevented them from setting up all the perimeters they had planned.

Impacts on Workers

Many companies reported supply chain impacts linked to a shortage of workers to drive trucks, fulfill distribution orders, and reopen retail outlets. These labor shortages arose from at least four factors. In some areas, companies were unable to communicate with workers and vice versa. Companies did not know where employees were and whether they were safe. Workers also faced transportation problems getting to and from work. More importantly, many workers needed to stay home to care for their families and repair damage to their homes. Finally, in the case of drivers, fears about driving into the storm or storm-affected areas influenced their willingness to work on the recovery.

Part of the challenge with workers is that supply chain jobs increasingly require more training and skills. Jobs such as operating a forklift, building a pallet, and driving a large truck cannot be done by just anyone. Unlike the military, which calls on reserve soldiers in times of war, private supply chains have no pools of trained workers that they can readily compel to work. Training a new hire can take six months. Thus, capacity of the supply chain may be limited to the number of people who are ready, willing, and able to get to work. Impacts on people have significant impacts on business and the ability to fulfill disaster-related surges of demand.

Impacts on Conveyances

Flows on the network lanes between nodes in supply chains depend on conveyances to move freight. Even if supply chain facilities are open, the roads are clear, and drivers are available, a shortage of conveyance assets can limit shipments. For over-the-road trucking, the two types of critical assets are trailers and the tractors that pull them. In the case of ocean container shipping, which transported freight to Puerto Rico, there were three types of critical assets: the container, the tractor, and chassis that provides the rear wheels and tractor hook-up for moving the container around the port and on the road. For the ocean leg of a journey, the critical assets were the containers and the ship (and also the chassis, in the case of barges). A great many participants spoke of the severe shortages of conveyances and time-consuming challenges of locating and acquiring freight capacity. At least four factors conspired to create a severe shortage of trucks, containers, and chassis during the three storms.

First, the halted pre-storm supply chain flows in Puerto Rico induced a cascade of logistical problems. Freight brought to the port in the course of ordinary business before the hurricane created severe problems after the hurricane. For example, after the hurricane, the ordinary freight such as lawn chairs had nowhere to go – the original customers for the freight either did not need it, could not take it, or were closed. As freight surged into the port after the storm, thousands of full containers accumulated at the port. Thus, thousands of containers became essentially stranded in Puerto Rico. Yet carriers depended on the timely emptying of these containers and their return to the mainland US to enable further shipments to Puerto Rico. Thus ports in Florida such as Jacksonville had a severe shortage of containers. As an added complication, ships serving Puerto Rico are designed to transport 53' containers, which maximize truck utilization on U.S. highways but are much less common than 20' and 40' containers typically used for global ocean shipping.

Second, imbalanced flows exacerbated the shortage of freight capacity. Typically, the economies of transportation mean that vehicle operators avoid taking loads to places that have no outbound freight, or backhaul, to areas near the origin. Without backhaul, the vehicle operator must bear the cost of moving the empty vehicle to a location that does have loads. Following the hurricanes, the depressed levels of economic activity in afflicted regions coupled with the surge of inbound

loads created exactly that type of imbalance.

Third, lack of fuel impaired transportation and recovery, especially in the cases of Irma in Florida and Maria in Puerto Rico. In both cases, problems arose in distribution of fuel more so than in supply. Florida faced high fuel demand associated with the evacuation and then challenges in distributing fuel back down the peninsula of the state (and reopening closed gas stations). In Puerto Rico, local fuel depots had 45 days of supplies (with more waiting off-shore), but distribution proved challenging under the combined effects of a driver shortage, damaged roads, and a surge in demand. The widespread use of generators (and the small sizes of their fuel tanks) meant that businesses and private citizens needed almost daily replenishment of fuel. Long lines contributed to a false perception of fuel supply shortages, which only further encouraged counter-productive hoarding and top-off behavior.

Fourth, participants spoke of competition between public and private sector shipments vying for limited transport capacity. The government shipments of water, food, etc. led to higher-than-normal demand for transportation at a time when the market was unusually constrained, in part due to factors above. Although public sector participants did not seek to control the limited capacity available for freight going into the affected areas, private sector participants reported having trouble securing truck, ocean, and airfreight capacity. De facto competition for capacity between government and commercial shippers occurred even if it was unintended.

Impacts on Power and Telecommunications

Both electrical power and telecommunications play a major role in supply chains. Electricity powers facilities, material handling equipment, refrigeration, etc. After the hurricanes, power outages plagued the storm-damaged areas, especially in Puerto Rico. Many participants mentioned the use of generators either to power entire facilities or to provide minimal level of functionality. Yet in Puerto Rico, the use of generators for weeks on end revealed the limits of emergency power systems designed only for short-term use. The generators had insufficient fuel capacity and required frequent replenishment. Much higher generator usage also led to unprecedented demand for maintenance supplies (e.g., parts, fuel filters) and repair technicians that were in short supply.

Telecommunications also play an essential role in supply chains. The lack of communications in some regions (especially in Puerto Rico) meant companies had no way of checking on the safety of employees or coordinating their return to work. One company in Puerto Rico noted that it took 10 days for it to contact all its workers. Telecommunications also play a crucial role in coordinating with suppliers, customers, and especially truck drivers. Moreover, many companies use remote electronic sensing systems to monitor facilities and control operations. With no power and no communications, companies were blind to the status of the facilities and unable to place orders for replenishment of depleted stock.

Commonalities and Differences among Critical Commodities

Discussions about water, food, fuel, and healthcare supplies revealed commonalities as well as differences among disaster-related supply chain issues with these critical commodities. For example, spoilage or contamination of products was a concern for many critical commodities. Spring water supplies were degraded by run-off. Flood waters ruined some fuel inventories in underground storage tanks, which delayed the reopening of gas stations until the fuel provider could bring in a special pumper truck to remove the spoiled fuel. Fresh and refrigerated food inventories in retail and distributor locations had to be dumped and replaced. Food and healthcare product companies had to check for water damage and ensure the sanitary integrity of facilities and inventory.

Survivor's daily need for water required shipping large volumes of this bulky material. Water also serves many purposes – drinking, cooking, cleaning, and bathing – boosting its importance. Government relief agencies did airlift some water, while companies expressed reluctance to do so on an ongoing basis for such a heavy item. Some companies airlifted water filters as a cost-effective alternative to deliver water.

Fuel was another bulky critical supply. If water was life giving to survivors, fuel was life giving to conveyances, generators, and other equipment needed to support the survivors and restart the local economy. Although much of the discussion focused on diesel and gasoline, alternative fuels such as LNG and propane were mentioned as potentially more robust because they rely on different supply chains and are less subject to demand surges.

Supporting survivors' food needs meant creating a supply chain of shelf-stable items and meals that could withstand the rigors of handling. But full recovery and the reopening of restaurants required restoring supply chains for perishable foods that need refrigeration or have limited shelf life. Companies mentioned having to make two key decisions with perishable

foods: 1) what to do with perishable but edible foods before or immediately after the event; 2) how to restock these items during the recovery.

In contrast to water, food, and fuel, the distribution of healthcare products had more constraints. Whereas everyone can drink the same kind of water, healthcare products come in many varieties that are highly specific to the patient and are supplied by highly specific manufacturers. Further, whereas water can be dispensed at will or sold in any retail outlet, the dispensing of many kinds of healthcare supplies such as pharmaceuticals can only occur under the supervision of doctor or licensed pharmacist. The healthcare supply chain spanned a more restricted and regulated set of facilities: manufacturers, distributors, clinics, hospitals, and pharmacies.

Participants mentioned many other unexpected critical items. Empty five-gallon containers (i.e., jerry cans) were mentioned in context of distributing both water and fuel. Such containers are lightweight to ship and enable consumers to collect and store bulk amounts of liquid. Cash was another critical resource in Puerto Rico. Banks were not open and, due to communications constraints, employees could not use credit cards to buy gas and supplies. So companies resorted to dispensing pay in cash. One participant was uncomfortable that the company had to bring in and manage so much cash. Other unexpectedly critical materials included generator filters and batteries.

Differences among Events

Geography and meteorology conspired to make the impacts of each of the three major 2017 hurricanes (Harvey, Irma, and Maria) different in the respective U.S. areas that they struck. Harvey, for instance, induced significant wind damage in the area of its first landfall. But rather than move onward inland and dissipate, the storm essentially stalled for 48 hours. As a result, unprecedented amounts of moisture from the Gulf of Mexico fell as rain on to the flat terrain around Houston. Substantial flooding damaged the area and impeded rescue and recovery efforts.

Irma's track took it straight up the Florida peninsula. Uncertainty about the east-west track and the potential effects on both coasts induced a large-scale, long-distance evacuation to the north. This evacuation congested the highway and depleted fuel supplies in the state. Following the storm, delivery of critical supplies to the southern part of the state was impaired by the need to first re-open and resupply the gas stations down the length of Florida. Irma also struck the U.S. Virgin Islands, which were largely supplied and economically linked to Puerto Rico, an island hit by the next storm.

Hurricane Maria intensified rapidly and made landfall in Puerto Rico as a Category 4 storm, decimating the power grid, cellphone towers, phone lines, and Internet connections across the island. Whereas the regions affected by Harvey and Irma were connected to extensive road distribution networks on the U.S. mainland, deliveries to the island of Puerto Rico were limited to sea or air. The extent of the damage to power, telecommunications, and road networks, combined with the rugged terrain of the island, resulted in repairs taking months; many areas still lacked connectivity as of the roundtable, 79 days after landfall.

Both private sector and public sector participants mentioned other disasters in talking about how organizations handle these kinds of events. Sandy (2012), for example, caused widespread power outages and fuel distribution problems up and down the East Coast. The 2011 Tohoku earthquake and tsunami in Japan devastated many suppliers of technological parts and material used by manufacturers around the world. Large forest fires, such as those in California in the fall of 2017, may not affect millions with the same devastation as a major quake or hurricane, but they do tax the region's supply chains due to the circuitous distribution routes induced by closed highways.

More generally, disasters can be characterized by when authorities can detect them, which then affects the ability to prepare for or react to the event. Some disasters (such as hurricanes) are detectable days before they strike. Others (such as earthquakes) are only detected at the instant they strike. And some (such as food contamination events or some kinds of cyber attacks) may not be detected until weeks after the initial cause, enabling these kinds of events to induce significant latent damage.

Solutions Employed

Throughout the day, representatives of the companies, government agencies, NGOs, and MIT described the tactics that they found to be helpful in handling disasters. Many organizations had similar approaches, although levels of adoption varied by organization and location. Overall, these practices encompassed a focus on supporting people, managing assets, and directing flows. Further research can help document the effectiveness of these solution practices, refine their definition, and identify the conditions under which they achieve especially good or poor results.

Preparation and Management

Many companies reported a range of preparations for the hurricanes as a way to reduce potential losses and accelerate recovery. Inventory-related preparations included pulling inventory from vulnerable locations and pushing inventory near the threatened region to cover the pre-storm and post-storm surges in demand. Companies also reported buying and preparing generators, including instances of very large flatbed units capable of powering factory production.

Some companies have established practices to adjust inventory rules in certain regions to provide a buffer for storms. A beverage company that experiences high demand every summer has a standard policy to continue its higher inventory levels for certain products in certain regions well past Labor Day to cover the hurricane season. That approach was sufficient to easily manage the first storm in 2017, though further intervention was required to cover the following storms. Companies also worked with their customers (e.g., distributors, retailers) to manage inventory as well as constrained post-storm logistics capacity. They worked to limit order inflation and to consolidate orders for transportation efficiencies. Communications with customers about inventory and order volumes helped dampen the noise.

Several participants extolled the virtues of satellite phones as a backup telecommunications platform. They were useful for facilities, suppliers, and truckers as a way to coordinate recovery activities when cellphone, landline, and Internet connections were down. Others found satellite phones to have poor reliability under some conditions, such as heavy rain and cloudy skies.

Finally, some organizations – both public and private – mentioned the importance of exercises or drills to improve their response to crisis. These kinds of exercises enable organizations to rehearse a pre-existing plan and can help managers and workers develop muscle memory for crisis events. Importantly, several participants mentioned how they also are used for discovery – uncovering unanticipated implications of potential disasters or creating new ideas for future plans. Scenario planning lets organizations play what-if to uncover surprises. Simulations and exercises can both practice the use of and create new checklists or playbooks that people then follow when a crisis occurs.

Supporting People

The resilience of a company depends on the resilience of its people. One of the best practices of resilient companies is to separate their efforts to take care of people from those that take care of the business. Creating parallel efforts for people and business ensures that neither effort suffers from a diluted focus.

Companies also noted that communications was a serious step-one challenge to supporting employees after the event and beginning the path to recovery. Companies often did not know whether employees had survived, been harmed, had evacuated, or were fine. Companies reported checking with the Red Cross, printing ads in newspapers, and sending company security personnel out to check on employees. Listening to employees and staying engaged with them helps guide support efforts and accelerate recovery of the community and business.

Support for employees extends to support for employees' families, because the health and safety of the family influences an employee's ability and willingness to work. Companies reported a wide range of family support efforts such as feeding employees, providing jugs of water for them take home, providing hotel rooms for displaced families, and giving out stuffed animals for employees' children. Drivers were an especially critical category of worker and companies found that supporting drivers' families before and after the storm improved drivers' willingness to move critical freight at crucial times into storm-affected areas.

Emergency Operations Centers

Many companies mobilize Emergency Operations Centers (EOCs), or "war-rooms", to monitor potential threats and coordinate activities in a crisis. During calm times, the EOC may be little more than a conference room with screens for presentations. But in an escalating crisis, these spaces ramp up into 24x7 operations hubs with real-time news feeds and information tracking.

A key element of EOCs is the choice of people in the room. Participants often include experienced managers functional groups that understand the internal aspects of the company, its products, and its customers (e.g., supply, logistics, pricing, sales, legal, facilities, operations). Resilient companies drive decision making down into the organization, which may be especially important if local facilities cannot communicate with headquarters in a disaster.

Surprisingly, the EOC membership of resilient companies tends to exclude the organization's top executives. Participants

said that crisis management calls for detailed operational knowledge and tactical decision making more so than strategic thought. Yet some participants cautioned that senior executives do need to be kept in the loop to avoid miscommunication and forestall independent and duplicative recovery initiatives. Given the complexity of many organizations and their supply chains, unstructured volunteerism leads to miscoordinated efforts and inefficient use of limited resources.

Government Support

Overall, FEMA's mission is to support the survivors in the aftermath of what may be the worst disaster of their lives. The agency's strategy has been said to be: go in big, fast, and smart to avert a true humanitarian catastrophe. Saving lives takes priority and, given the unknown scale of any event in the early hours, it makes sense to estimate worst-case demand for relief supplies. In many cases, the agency's direct aid only needs to last for a week or two before retailers and other businesses reopen. But in Puerto Rico, the extent of the devastation necessitated that FEMA was still serving over a million meals a day as of the roundtable, the 79th day after the hurricane. The strategy of surging entails necessarily large orders of critical commodities such as water and food, which is a significant surge in freight movement into the affected area. As such, FEMA can require significant transportation capacity in a very short time to do its job.

Yet the agency also seeks to "do no harm" and to accelerate the recovery of the local economy to pre-disaster levels of functioning. In that regard, the best aid beyond that initial surge of the emergency is to get people, companies, and the economy back on their feet so that people are back at work, getting paid, and doing their everyday jobs that support the everyday economy. That implies working with businesses to accelerate their recoveries.

The NBEOC (National Business Emergency Operations Center) was created in 2012 to provide an interface for federal agencies and private sector actors through various communications channels including online dashboards, coordination calls, and liaisons. In the past, the NBEOC and DHS (Department of Homeland Security) hosted separate status update calls with the private sector, which resulted in some duplication of information. During the 2017 disasters, the two agencies merged their calls to create a unified daily status briefing call. Calls had as many as 1200 participants on the line. Thus, the mechanism served as a very important aggregator and disseminator of information on the situation and recovery efforts.

Finally, temporary waivers of regulations by various government agencies boosted logistics capacity and logistics-related supplies. In particular, many participants lauded the government's waiver of HOS (Hours of Service) regulations. Permitting drivers to work more hours enabled them to carry more loads, drive further, and make more deliveries. This helped cope with the "perfect storm" combination of surging demand, limited driver availability, and congested or degraded roads. Similarly, the Environmental Protection Agency's (EPA) regional waivers of several types of fuel specification requirements helped boost supplies in hurricane-affected areas.

Flexible Networks

A net effect of preparations, support for people, EOCs, and government support was that a number of companies changed how they managed their networks to cope with the effects of the disasters. For example, companies modulated the deployment of their resources so that they could simultaneously serve the surge in the affected areas while maintaining service to the rest of the country and world. Typically, companies have geographic networks of facilities (both manufacturing and distribution) by which each regional facility serves that region's demand. But in cases of disrupted facilities or surges in demand in the affected areas, companies can shift their patterns of service. For example, a facility in south Georgia might be retasked to serve Florida, while a facility in South Carolina might be retasked to serve Georgia, and so on. These shifts add hundreds or thousands of miles to the travel distances of goods but helps ensure goods reach their destinations. These efforts also faced challenges, such as differences in the types of items made, stocked, and sold in different regions, as well as the pre-existing supply and demand imbalances that limited flexibility.

Corporate aviation jets were another private sector asset deployed during these disasters. Although corporate aircraft have negligible freight capacity, they have extremely high flexibility in being able to operate out of around 5,000 smaller U.S. regional airports. They were used to bring in high-value, lightweight cargo such as medical supplies and emergency repair parts. They also carried crucial passengers such as medical evacuations and specialized experts (e.g., technicians to repair emergency telecom networks or generators in Puerto Rico). A related use of local aviation assets was the use of helicopters in Houston to ferry supplies to hospitals stranded by flood waters.

Several participants mentioned the practice of mutual aid between competitors in times of disaster. Some saw it as a matter of good sportsmanship. Others noted that a common enemy (i.e. the hurricane) motivated collaboration between

would-be commercial enemies. Regardless of motivation, the sharing of resources and coordination of efforts enhanced the strength and recovery of the industry.

Opportunities for Improvements

During the overnight break between the two event sessions, participants were asked to think about the kinds of data and relationships they would need to provide greater resilience. The next morning, the group discussed supply chain dependencies, network effects, data, analytics, and resilience strategy. These discussions, as well as organizations' stories of frustrations or problems experienced during their response to the crises, defined a set of potential opportunities that could lead to faster, better rates of recovery during future disasters. The wide-ranging nature of challenges that different organizations faced during the three hurricanes suggested there was a need for a better collective framework to incorporate what seemed like ad hoc variables.

Map and Understand the System

A key first step to resilience is in mapping critical supply chains and critical infrastructure to understand where critical goods (and their essential ingredients) come from and how they might move down the chain to an area affected by disaster. Foreknowledge of the fragile facilities and vulnerable connections, as well as possible alternatives, can accelerate both the assessment of and implications of a disaster and the recovery. Moreover, part of this mapping entails measuring the system's conveyance capacity such as tractors, trailers, containers (of various sizes), and compatible chassis. Baseline measurements of logistics activity during normal times provide both a benchmark for recovery and an approximate indicator of likely capacity in a crisis.

Some companies already map their supply chains as part of their risk management and resilience efforts. These companies use the bill-of-materials (BOMs) for products and corporate accounting records regarding procurement of these materials to understand the implications of supplier disruptions. Thus, the company can determine which products and customers would be disrupted if a given supplier were disrupted. Companies can use third-party supply chain risk management services that help gather information on suppliers' geographic locations. These services can also utilize real-time news feeds for impactful events to alert companies how a given distant event might affect them. Using the BOM and data on the revenues or profits from each product, companies can even estimate the potential financial magnitude of a disrupted supplier.

These maps can help reveal not only the obvious ingredients but also the incidental materials that may be just as critical. Based on examples mentioned in the discussion, such maps might show that helium is crucial to hospital MRI machines, that plastic resin is essential for water bottle manufacturing, or that fuel filters are required to keep emergency generators running. For the most part, these supply chain maps are visible only within private companies, even though they might greatly assist national preparation and response to disasters. More sophisticated analyses could reveal coupling between critical infrastructure and critical commodities, such as how the loss of the power grid might induce a surge in fuel consumption in private generators.

Some participants sought to identify the single-most important supply chain element in the system – what one participant termed the "belly button" – where a modest poke or intervention can forestall a cascading collapse. Others, however, lamented that the system seemed to consist of bottlenecks inside bottlenecks inside bottlenecks: more like a Russian nesting doll or a whack-a-mole game. Drivers, trucks, containers, roads, telecommunications, fuel, power, and more were all equally-important elements in the system. Shortages or reduced capacity in any of these subsystems created shortages or reduced capacity for the entire system.

Assess Criticality within the Local Context

This roundtable focused on a limited set of critical commodities to stimulate discussion, but did not attempt to document or prioritize all of the critical supply chains. Moreover, the stories from these 2017 events indicated that locality affects what is considered critical to recovery. For example, tourism is an essential component to the economies of both Florida and Puerto Rico. Although "entertainment" does not seem like an essential service, power restoration efforts in Puerto Rico prioritized hotels because of their critical role in the island's economy. Understanding the local economy and the priorities of local authorities is a key aspect in preparing for recovery in the event of a disaster.

It was mentioned that understanding the local context and the supply chains that support local markets is increasingly important for international disaster relief organizations as they move from direct aid (food, water, etc.) to cash assistance.

They are doing so for two reasons. First, direct aid can be misaligned with local preferences. For example, direct aid might unintentionally distribute food items that locals do not prefer or know how to cook. Second, direct aid displaces local providers of these goods, thereby harming the local economy. In contrast, cash enables survivors to buy what they prefer from local providers. Thus, cash can both improve the quality of aid and help restore the local economy. However, if local suppliers do not have the capacity to serve survivors' needs, then cash aid could cause rapid price inflation and reduce the purchasing power for consumers who were not given a cash handout. Therefore, the strategy depends on understanding the dynamic capabilities of local supply chains.

Create Better Situational Awareness

In the aftermath of a disaster, governments, companies, and citizens desire real-time data on the status of a wide range of public and private resources. Examples include road closures, shelters, aid distribution points, and the status of retailers such as grocers, pharmacies, and gas stations. Companies and government agencies want real-time data on supply chain status that encompasses transportation infrastructure, the facilities of upstream and downstream supply chain partners, conveyance capacity, and the flow of goods in the network. During the 2017 events, manufacturers and distributors had problems making requested deliveries to distributors and retailers, respectively, because they did not know which customer facilities were open and when they might be able to take deliveries. In the case of transportation infrastructure, companies had no single source of information about the reopening of corridors or ports. Some companies reported that only some state DOTs (Departments of Transportation) published good maps, and that the companies had no unified view at the national level. Planning truck routes across state lines meant comparing and connecting different types of state-level maps.

A number of both private-sector and public-sector participants mentioned the challenge of matching ad hoc supply with ad hoc demand. In a disaster, aid agencies reported being inundated with both offers and pleas for aid. And companies reported having surplus resources that could be deployed if they had a way to find a suitable user. One proposal was to create a registry: a unified interface for offers of available capacities or supplies and requests of needs. In addition to clearly specifying the offer or request, the registry would need to track whether the offered item was free, on loan, or involved some nominal cost. Such registries have been proposed and even built in the past, but adoption has been stymied by a combination of legal, financial, and ownership issues.

Both private and public sector participants sought better insight into the importance of supply chain activities, such as orders and shipments, relative to the goal of recovery in the affected region. For example, private companies wondered whether orders from retailers, NGOs, and even government aid agencies represented critical requests, normal replenishment, or ghost orders. Sometimes in the heat of the moment, various parties might send out emergency requests to multiple potential suppliers for large quantities of supplies. The result may be duplication of orders or submission of just-in-case orders that are ultimately not needed but do accumulate in the supply chain. Similarly, public authorities who may be regulating access to unsecured areas or to degraded congestion-prone road networks want to know whether an incoming truck contains critical supplies needing immediate delivery, normal commercial replenishment that could be delayed, or unauthorized personnel. For both private and public organizations, prioritizing their supply chain activities depends on knowing the purpose of those activities, and on building consensus around what is "priority"

A key challenge to better planning and visibility is that much of the important data about infrastructure and supply chains is security-sensitive government data or proprietary company data. The group identified the unsolved challenge of sharing sensitive data as an obstacle to visibility, coordination, and crisis management. The government does have some mechanisms by which companies can share proprietary data that would not be vulnerable to sunshine laws like the Freedom of Information Act. But a missing piece is how business and government can readily coordinate on the broader use of such data or information derived from the data. Government information related to critical infrastructure remains a sensitive topic. FOUO (For Official Use Only) was an over-used four-letter word that harmed recovery, according to some participants. For example, one company expressed frustration at not being able to gauge when power might be restored because the map of the power grid was classified and thus unavailable. Yet the company did not actually need the sensitive map data as much as it needed an estimate of restoration, suggesting that sensitive data could be converted into actionable information.

Visibility regarding infrastructure restoration times would help companies and public planning of aid delivery. Not knowing whether electrical power, for example, would be restored in three days or three months makes management of the recovery much harder. The anticipated duration of infrastructure disruptions influences whether and how companies plan for contingencies such as: (1) waiting for restoration, (2) deploying a short-term partial solution, e.g., small generators to

power initial recovery and partial operations, or (3) seeking a longer-term, full-scale solution, e.g., large capacity generators to power an entire factory for weeks or longer.

After Sandy (2012), many gas stations were closed in the New York metropolitan area. Those needing fuel for cars, trucks, or generators had no easy way to find the nearest open gas stations. A group of New Jersey high school students created a way to crowdsource data about which stations were opened or closed. Although this enterprising effort shows the potential power of social media and new technology to gather and publish large amounts of real-time information at low cost, the example also highlighted two issues. The first was the naturally different standards of information validation between the crowdsourced solution and the more methodical government data collection, analysis, and dissemination. The second was the potentially dangerous dynamics by which publication that a given site was open might prompt excessive crowding at that location. The crowdsourced system could say if a gas station was open but not how much fuel it had to serve a potential onslaught of new customers.

Develop Indicators and Analytical Products

Although private-sector and public-sector participants desired detailed real-time data, they also recognized the impossibility of such a task. The challenges of data-gathering in a crisis brought up the suggestion of using indicators or proxies for potential supply chain problems or supply chain health. For example, in trucking, the spot market could be a useful indicator even though it represents only 15% of total volume. Although a functioning economy offers myriad products and services, one government participant mentioned using a simple set of indictors for the economy measuring whether workplaces are open and the availability of ATMs, gas stations, chain restaurants, and milk. The proper construction of easy-to-collect but actionable indicators was identified as an open issue.

Indicator values could come from "sentinel" data sources. Rather than attempt to collect information from every possible location, data gatherers could focus on rigorously select entities or facilities as proxies or statistical samples of what is occurring in the broader supply chain or community. Sentinel indicators are used in the public health community. For example, health organizations monitor influenza by regularly tracking data from a small subset of "sentinel" hospitals and clinics. Data from a properly designed sample can provide early warning or approximate indicators for a community without the cost of more intensive data collection.

Further research and analysis of critical supply chains could help identify suitable sentinel or other low-cost, high-quality indicators of hard-to-collect data. For example, one NGO was using real time prescription-drug claims data that pharmacies submit to insurance companies as a proxy for the open/closed status of the pharmacies. Rather than contact hundreds or thousands of pharmacies or expect every pharmacy to send status data to a central location, the NGO could estimate the status of each pharmacy by the outlet's activity with a single organization: a claims processor.

There was discussion regarding how the interplay among fuel, drivers, and transportation equipment is a nexus that might offer "sentinel indicators" that span supply chain system status more broadly. Comments indicated that truck transportation is optimized to an implicitly assumed persistent equilibrium and that disruption can quickly introduce constraints, which may have unforeseen cascading effects. If fuel and/or trucking are insufficient to meet transportation demand, then the network will be increasingly stressed and unable to fulfill commodity demand.

At the roundtable, MIT researchers shared a handout that provided analysis of freight through the port of San Juan, Puerto Rico, prior to and following the hurricane. This node would clearly be a "sentinel indicator" of supply chains supporting the island. Combining various data sources, the handout provided some useful insights. But more importantly, it demonstrated the information gathering challenges that plague disaster recovery. These problems included differences in terminology among port-related companies, contradictions in data from various sources, misleading data that induced some observers to misdiagnose problems, and significant instances of missing data about critical port operating levels. Discussion indicated strong interest from public and private sector participants in the ability to conduct such analysis, showing the value of readily available data and analytical products to understand supply chain capacity.

Confounding the issue of data availability, information sharing, analysis, and the use of indicators is the question of confidence. The government tends to take a "validation before dissemination" stance. The view is that, if companies, local authorities, and citizens are going to use government provided data or analysis to make crucial and costly decisions, then the information needs to be fully accurate. However, thorough validation takes time or may not be possible, which, in turn, delays action. Lack of timely information fosters the spread of inevitable misinformation that fills the information vacuum. With the 2017 hurricanes, this included varying perceptions that the Jones Act was limiting shipments to Puerto Rico. The

ability to rapidly disseminate relatively-accurate port analysis, such as that mentioned above, might have led to better decisions than those based on anecdote and speculation. The key requirement is effective communication regarding the relative accuracy of information. There was broad interest in developing approaches to characterize the confidence or accuracy of data and analysis in ways that enable recipients of partially-validated data to act with proportionate caution.

Develop Relationships

Many participants from both private and public sectors stressed the importance of pre-established relationships. Connections established before a crisis accelerate coordination during the crisis. Better relationships in conjunction with better data can improve resource sharing and utilization while also informing temporary interventions such as prioritization, allocation, and regulatory changes.

Improved resource sharing begins with awareness of capacity. Interestingly, both public and private sector representatives cited the impressive depth of resources available to the other side. The collective physical assets in private sector supply chains dwarf those of the government, and the government's information gathering and oversight tools provide them information resources with a much broader view than any single company. With common awareness, resources could be shared or at least managed more effectively in supply chains. Some strategies could be developed prior to events. Therefore, many in the room advocated much greater public-private collaboration to both prepare for disasters and to manage crises.

There was discussion regarding how collaboration should not be limited to information sharing but also involve joint problem solving. This requires the right mix of people in each organization. The question of who should be involved in the "emergency operations center" or "war room" depends on the organization. Research indicates that decision making during crisis is an iterative approach between framing a problem, solving a problem, and then reframing the problem with new information including results from previous solutions. It may not be clear that senior leaders have the bandwidth to engage in rapid, iterative efforts that dynamically frame and reframe problems, leading to more effective decisions. This process also emphasizes the importance of analysts and interpreters of data who can quickly frame problems and/or develop effective analytical products like those mentioned above.

Several interventions were mentioned as a result of improved relationships. For example, a better understanding of supply chains could help guide priorities for key response and recovery efforts such as infrastructure repair, road clearance, power grid and telecommunications restoration. Better public-private relationships would also help modulate real-time prioritization and allocation in the face of unexpected needs (generator fuel filters) or non-obvious critical supplies (helium for hospital MRI machines).

Better coordination processes could also guide relaxation of regulatory restrictions in areas such as those mentioned above regarding driver HOS (Hours of Service) and fuel specification. And if supply chain capacity is limited by shortages of drivers, vehicles, chassis, containers, inventory storage, road capacity, port capacity, or other critical resource, then better knowledge and data would help prioritize the utilization of that scarce capacity. Communication to improve broader awareness is critical since interventions such as prioritization or allocation are only effective if they do not have unintended consequences elsewhere in the system, which may end up doing more harm in the overall response and recovery.

Three changes emerged as paths to improve relationships and coordination. *First, both public and private-sector participants wished for more uniform interfaces or clearer roles for these relationships.* Public-sector representatives faced challenges with a diverse flow of requests via multiple channels. Private-sector participants were often unsure whom to contact and for what, leading to a fragmented pattern of requests. Uniform interfaces would help formalize coordination of public-private joint activities such as access and support. For example, police escorts and crowd control efforts helped expedite some critical shipments of fuel and helped control crowds at some gas stations, but it was not evenly managed. Uniform interfaces might also employ a set of common service definitions related to warehousing and trucking. There also need to be common approaches to subdivide coordination across broad community needs. The Business EOC in Puerto Rico was organized around business segments rather than the 16 DHS critical sectors; a "cross sector council" was also established quickly. It was noted that private sector supply chain resilience initiatives are typically organized around industries. Coordination frameworks need to make sense in both the public and private sector.

Second, several comments hinted at the need for better multi-jurisdictional coordination both spanning the geographical scope (national-state-local) and among agencies within a jurisdiction. During 2017, for example, some statements made by federal agencies were misinterpreted as granting access to areas being managed by local authorities. In another example,

operators of corporate aviation relief flights could not determine which agency should give them landing permission because each agency claimed the other was in charge. Delineating jurisdictional control and creating clear processes for inter-operation of business and government activities would avoid problems such as access restrictions that further degrade critical supply chain flows and capacity. Other stories suggested that this coordination could be difficult due to differences in culture, priorities, and how each agency views the issue.

Third, better joint exercises or rehearsals would help build relationships, clarify roles, and discover gaps in business-government coordination mechanisms. Table-top exercises can help groups challenge assumptions, pre-negotiate responsibilities, and understand the priorities and capabilities of each party. The goal of all these improvement efforts that build better relationships and coordination is to foster joint problem solving considering the combined resources of both the private and public sectors.

Resilience in an Unknown Future

In 2017, three major disasters struck the U.S. and its territories in sequence. Although that seems unprecedented, one participant claimed that it has actually happened three times in the last 12 years. A recent MIT study, published in the Proceedings of the National Academy of Sciences, reports that the state of Texas had a 1 percent chance of experiencing rainfall of Harvey's magnitude for any given year between 1981 and 2000 but by the end of this century, the annual probability of Hurricane Harvey's record rainfall returning to Texas will rise to 18 percent. Despite perceptions, 2017 was not an outlier.

The biggest disaster is always in the future. The past is bounded by the given magnitude of historical disasters but the future is unbounded. Statistics all but guarantee that the worst has yet to happen. Added to this mathematical inevitability are social and economic trends such as urbanization and greater supply chain interconnection.

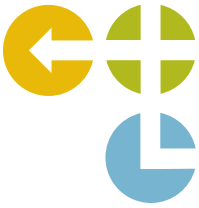
New ways of modeling unbounded future risks were presented and discussed at the roundtable. The insurance industry increasingly complements traditional actuarial approaches with models that link risk and vulnerability. They go beyond estimating expected annual loss to extrapolate various impacts of future events. Models can estimate the probability that losses exceed some target value in future decades, but they can be also used to guide provision of worst-case buffers, from capital for insurers to logistics capacity for disaster relief. Other models can determine a risk score for individual shipments and be used in real time to shape shipping and routing patterns. Such models show how larger volumes of data and novel analytical approaches enable more sophisticated risk management and can guide proactive and reactive resilience activities for multiple time horizons.

Beyond models that better anticipate the future, resilience must leverage insights from the past to better prepare for the future. The roundtable discussions based on stories from 2017 contributed several insights and identified some key themes.

- *The fragility of optimized networks.* The three hurricanes disrupted flows in supply chains more so than they damaged supply. Lean pools of conveyances that are optimized to maximize efficiency during normal times leave no slack to adapt during a crisis. This fragility is likely to increase as companies are more inclined to further optimize networks than to invest in slack. Thus, early information regarding potential bottlenecks, such as "sentinel indicators", will be essential in scaling critical supply networks during crisis.
- *Deep coupling of human and technological systems.* Without drivers, critical commodities like food and water cannot be distributed. And yet, without food and water, critical employees such as drivers and workers across the supply chain will need to address their family needs above their role in moving and distributing goods. Trends such as how the aging demographics of truck drivers and new regulations around electronic logs for hours of service may further constrain transportation capacity. Coupled systems and trends such as these should be incorporated into preparedness planning.
- *The potential cascading effects of supply chain failures.* The stories from 2017 reiterated importance of supply chains that are required to operate supply chains, such as fuel and repair/maintenance parts. Many contingencies that lead to cascading effects are hidden during normal operations and are only realized during crisis. Going forward, preparedness efforts need to explore the nature of supply chain contingencies and cascading effects in order to create more resilient plans.

Tomorrow's crises will be different than the past. The dynamic nature of the global economy and ever evolving threat matrix will continue to change the context. New technology may obviate some threats (e.g., satellite internet that is not reliant on fragile wired networks) and create others (e.g., cyber-security threats). Given this changing context, federal

agencies must continue to evolve the definition of "critical infrastructure" and understand how requirements must change. This roundtable contributed productive discussions based on recent experience to guide progress down this path. Through careful study of critical supply chains, researchers, business executives, and government leaders can understand how to prepare for this uncertain future and strengthen the systems to be more resilient and better managed for a faster recovery during crises.



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