Strengthening Post-Hurricane Supply Chain Resilience

Observations from Hurricanes Harvey, Irma, and Maria

Photo: Michael Seeley, Wikimedia Commons

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The Federal Emergency Management Agency (FEMA) asked the National Academies of Sciences, Engineering, and Medicine Committee on Building Adaptable and Resilient Supply Chains After Hurricanes Harvey, Irma, and Maria to analyze the function of supply chain networks in four primary areas affected by the 2017 storms in South Texas (Hurricane Harvey), South Florida (Hurricane Irma), and Puerto Rico and the U.S. Virgin Islands (Hurricanes Irma and Maria). Specifically, the committee was asked to identify key lessons from these events related to supply and distribution networks and to offer recommendations for improving the conveyance and distribution of essential supplies and commodities during disaster response and recovery operations—focused on supply chains for food, fuel, water, and pharmaceutical and medical supplies. This article highlights parts of the report that focus directly on transportation issues in the four localities previously mentioned.[1,2]

Above: Ominous clouds—Hurricane Irma's outer bands—draw a crowd to Florida's Satellite Beach to watch the storm come in. The next day, Irma made landfall in the Florida Keys, affecting most of the peninsula and bringing storm surges, severe flooding, tornadoes, and disruptions to moving goods along linear truck routes.

Supply chains facilitate the timely flow of materials and products from suppliers to manufacturers to distributors (wholesalers) to distribution channels (e.g., retailers, clinics and hospitals, and nongovernmental organizations) and, finally, to end users. They do this by transmitting demand information upstream—and other related information downstream—to guide production, transportation, and distribution decisions.

[1] To view the entire publication, visit https://www.nap.edu/catalog/25490/.
[2] To view a digital interactive summary document of the publication, visit https://www.nap.edu/resource/25490/interactive/.

Disruptions to a supply chain can result from several forces, including demand shifts (e.g., spikes in demand for fuel and bottled water), capacity reductions (e.g., when a factory or retail store cannot operate due to damage or power outages), and communication disruptions (e.g., loss of cell phone, Internet, or point-of-sale systems). The resilience of a supply chain depends on how its bottlenecks and lead times are affected by such disruptions and what capabilities exist for swift restoration after a disruption. The objective of supply chain resilience is to minimize the impact of such disruptions on the affected population.

The Hurricanes

HURRICANE HARVEY

Harvey made landfall as a Category 4 storm on August 25, 2017, with winds reaching 152 miles per hour and storm surges ranging from 5 to 10 feet. Most initial wind and wave damage affected the Coastal Bend area on the Gulf of Mexico, with flooding occurring when the storm made a second landfall and stalled over Houston—during which time the region received more than 50 inches of rainfall. Massive flooding occurred across Houston, Beaumont, and many other southeast Texas communities.

HURRICANE IRMA

Irma reached hurricane strength on August 31, 2017, and by September 5 it had intensified, with sustained wind speeds of 185 miles per hour, becoming the strongest hurricane ever observed in the Atlantic Ocean. Irma maintained Category 5 winds for three days as it moved west, slammed the U.S. Virgin Islands, and knocked out Puerto Rico's fragile, aging electrical power system. On September 10, Irma made landfall at Category 4 strength in the Florida Keys. Tropical storm–force winds extended outward up to 400 miles, affecting nearly the entire Florida peninsula. As Irma advanced across Florida, severe flooding, storm surges, and tornadoes occurred across numerous counties.

HURRICANE MARIA

On September 19, 2017, Maria passed over St. Croix in the U.S. Virgin Islands, destroying much of the island's buildings and communications and power infrastructures. On September 20, Maria made landfall in Puerto Rico at Category 5 strength, dumping more than 30 inches of rain. By the time the hurricane weakened, the entire island's power infrastructure had been destroyed and 100 percent of customers had lost service.

Defining Geographical, Supply Chain, and Modal Characteristics

SOUTH TEXAS

Houston is highly flood-prone because of low elevation and flat topography, which offer no natural physical drainage pathways for intense rainfall. During Hurricane Harvey, the city's bayous and drainage systems quickly filled, leading to rapid flooding of freeways and roads. These flooding risks have been exacerbated by sprawling development patterns that displaced wetlands and other green spaces with impervious concrete and asphalt surfaces. The Texas coastline is long and exposed but accessible from inland areas and, thus, not dependent on water-bound shipments for relief efforts. At the same time, the region's widely dispersed development patterns mean that the distribution of goods and services requires considerable, reliable road transport capacity. When roadways

Photo: Unsplash

Cars parked curbside bring a strange sense of order to the chaos of flooded streets in a southeast Texas community, the result of Hurricane Harvey's second landfall in late August 2017, when the storm stalled over Houston. More than 50 inches of rainfall brought massive flooding across Houston, Beaumont, and many other communities in the region.

Photo: Holly Ireland, Pixy

Connecting to part of the Port of Houston, one of the world's busiest seaports, the 52-mile Houston Ship Channel is an important maritime transportation link. Despite the city's well-developed multimodal infrastructure with connectivity and redundancy through rail, truck, barge, ship, and pipeline, the ship channel is a potential point of failure for a critical distribution network.

are cut off by flooding, normal supply chain systems quickly become paralyzed.

The Houston area has a well-developed multimodal infrastructure with substantial connectivity and redundancy through rail, truck, barge, ship, and pipeline options. The area has plentiful capacity in its multimodal transport links and its highly interconnected, multidirectional corridors. Road and rail transport nodes are relatively dispersed. But for maritime transport, the Houston Ship Channel is a critical transportation link and potential single point of failure for a critical distribution network.

FLORIDA

Much of Florida is prone to flooding due to low elevations and development patterns that undermine natural drainage systems. South Florida has underlying porous limestone that allows floodwaters to arise from underground and has coastal exposure to Atlantic as well as Gulf Coast storms. As an 800-mile-long, densely developed peninsula with just a few main transport corridors, Florida's geography exacerbates challenges during mass evacuations from vulnerable areas along congested routes or large-scale delivery of critical goods and services into affected areas. Hurricane Irma caused record-breaking rapid evacuations along congested highway routes. Relief supplies can be sourced from outside the state, but truck drivers must still navigate the peninsula to deliver goods and services, with the uncertainty of when they will be able to return home. Fuel delivery to Florida is primarily by water to port facilities, where it is distributed by tanker trucks.

Truck transport is the dominant mode for most goods, except for petroleum products that arrive primarily by ship. This is augmented by limited rail capacity. Florida is more limited by capacity than South Texas because of its linear, parallel transport links that predominate along the peninsula. Refined petroleum distribution for a large market is concentrated at a limited number of fuel distribution points.

PUERTO RICO AND THE U.S. VIRGIN ISLANDS

Puerto Rico and the U.S. Virgin Islands are grouped together because they share many common characteristics. These islands rely entirely on delivery of goods and relief supplies by ship and barge, primarily from U.S. ports more than 1,200 miles away. Transit times and delays for delivery of goods are an important factor in emergency response planning. Puerto Rico has one large natural harbor (the Port of San Juan, a critical node for most supply chains), plus other smaller ports around the island. The island's mountainous terrain poses challenges for emergency response and goods delivery.

On the island of St. Thomas in the U.S. Virgin Islands, the main industrial port has limited space for unloading shipping containers and staging of large-scale relief supply deliveries (which elevates the likelihood of bottlenecks). And there is even less port capacity on the other islands. Evacuation from an island requires considerable advance planning.

Most goods arrive by ship. Within each island, only truck-based distribution originating at the port of entry is available. Puerto Rico is characterized by circumferential routes around its perimeter. The U.S. Virgin Islands are capacity-constrained by a small number of roads on each island. As a result, people living in isolated inland locations faced severe problems with delivery of critical goods. Both islands have a single port of entry for the majority of supplies imported to the islands, ports that represent critical nodes as well as potential bottlenecks.

Supply Chain Disruptions

TEXAS

Distribution and delivery services for food, bottled water, and other critical goods were interrupted for more than a week when flooding from Hurricane Harvey made road deliveries impossible. But as

Photo: Andrew Heneen, Wikimedia Commons

On the move ahead of Hurricane Irma, residents of the Tampa, Florida, area take advantage of governor-authorized emergency use of the left shoulder along eastbound Interstate 4 toward Orlando. Florida's linear geography—with only a few main transport corridors—poses challenges during mass evacuations and has an adverse effect on large-scale delivery of necessary goods and services.

Photo: U.S. Navy

Strong partnerships and teamwork come together as a U.S. Navy sailor directs a U.S. Army tactical vehicle off a landing craft in St. Thomas, U.S. Virgin Islands. Such cooperation—between service members, as well as civilian responders—was critical to assessing damage and administering relief following Hurricanes Irma and Maria.

Photo: Spc. Agustín Montañez, Puerto Rico National Guard

After Hurricane Maria devastated Puerto Rico, leaving the island flooded, without power, and in a tangle of debris and downed trees, the Puerto Rico National Guard set out to clear blocked roads as quickly as possible. The island's mountainous terrain exacerbates problems with prompt delivery of disaster relief.

waters receded, most grocery stores quickly recovered and reopened. Texas and Louisiana are major fuel-producing hubs, so sustained closure or damage at these facilities can have widespread effects on fuel supply chains, involving critical production nodes and transportation links. During and immediately after Harvey, closure of all major ports along the Texas coastline affected approximately 25 percent of Gulf Coast offshore oil and natural gas production and approximately 50 percent of Gulf Coast refinery capacity.

Supply chains in the South Texas region proved largely flexible and resilient but illustrated that systems will have great difficulties functioning when flooding is too severe and critical infrastructure is damaged. Thus, investments in sustainable development patterns that minimize flooding problems—through, for example, elevating critical roadways and minimizing impervious surfaces—are priorities for building resilience.

FLORIDA

With a long history of hurricane landfalls, Florida has well-organized systems for disaster preparedness and response. Yet Hurricane Irma illustrated limitations and vulnerabilities in current systems. For instance, one vulnerability was the difficulty of maintaining an inflow of supplies in the face of serious transportation bottlenecks caused by fuel limitations, traffic backups, and lengthy deadheading return trips (trips made by truckers pulling an empty trailer with no cargo, thus generating no revenue). Another vulnerability was poor coordination in the movement of trucks and supplies across state lines in the face of information disruptions and communication problems.

Florida has almost no fuel production facilities; rather, it receives the bulk of its fuel from the Gulf Coast region and foreign imports. When Irma approached, most major Florida ports and major petroleum marine terminals temporarily closed. Such short-lived closures did not themselves cause major supply problems. But an array of fuel problems did arise, initially stemming from the evacuation of more than 6 million people and the resulting surge in fuel demand, which caused bottlenecks at many fuel stations.

PUERTO RICO

In the aftermath of Hurricane Maria, many of the post-hurricane supply chain challenges were at the Port of San Juan. Cargo made it to the port, but imported goods could not be processed effectively because of sustained power outages. Then, once processed, many goods could not be removed from the port area because of blocked roads and shortages of trucks and drivers. Thus, the port quickly became overwhelmed as large loads of relief supplies poured in.

Many communities in Puerto Rico faced food shortages and initially were dependent on relief supplies. Grocery stores were adversely affected when truckers were lured away from their normal jobs to run relief supplies or wait at the port. Petroleum terminals were shut down and fuel stations were temporarily closed, but there were no reports of serious shortages of gasoline. Other problems related to fuel distribution included power outages

that prohibited the processing of some fuel shipments and prompted the need for security escorts for the tankers. As one positive example of preparedness, the island's propane and liquefied petroleum gas supply and distribution proved resilient because the largest supplier was prepared to sustain the operations of its delivery terminal, storage facilities, truck fleets, and networks of drivers.

U.S. VIRGIN ISLANDS

The U.S. Virgin Islands were greatly affected by both Hurricanes Irma and Maria. Some of their challenges were similar to those in Puerto Rico in terms of being dependent on ship and barge imports for food and other critical goods, and on aging, fragile infrastructure.

The islands also faced unique challenges such as the complexity of meeting the needs of affected populations on three islands (*1*). There were no widescale reports of food shortages, but curfew hours imposed on residents—coupled with damaged and congested roads—made it difficult for many residents to find time to gather needed daily supplies. Despite these challenges, FEMA and others operated relatively efficiently in conveying some critical relief supplies, partly because of the smaller population and fewer communities that needed assistance.

Common Factors and Lessons Learned

Even with the diverse contexts and experiences of the storm-affected areas, there were some common pre- and post-hurricane challenges that unfolded, pointing to lessons to consider moving forward. One lesson is that post-hurricane bottlenecks and disruptions arose more frequently at the distribution level than at the production level. This is in part because distribution occurs within the affected region, while much of the production often occurs elsewhere. In addition, distribution is often carried out by smaller businesses and organizations with less preparedness capacity than large companies have.

Another lesson is that some of the most common factors underlying these last-mile distribution challenges were shortages of trucks and drivers for goods delivery, shortages of other personnel that occurred when workers became storm victims, and damage to critical infrastructure that impeded distribution and selling of goods. Uncoordinated, unsolicited donations sent to affected areas were another common source of bottlenecks at the distribution level. Dealing with these donations drew critical resources (e.g., volunteer efforts and storage space) away from more strategically targeted needs.

Recommendations

The committee proposed four overarching recommendations for advancing the United States' capacity to provide critical supplies to affected populations in the aftermath of hurricanes:

1. **Shift the focus from pushing relief supplies to ensuring that regular supply chains are restored as rapidly as possible through strategic interventions.**

To advance this recommendation, the committee suggested prioritizing recovery of infrastructure critical for resuming normal supply chain operations. Critical infrastructure (e.g., power, transportation, roads, bridges, and water) enables operation of all supply chains. In most cases, adequate supplies of materials existed in the areas affected by disasters, but the ability to ship and deliver those supplies was impeded by lack of roads, trucks, drivers, fuel, or electricity. Repairing and rebuilding damaged infrastructure is not seen as FEMA's direct role, but the agency could be well positioned to take a more active leadership role in aiding such efforts.

The traditional focus on bringing relief supplies to an affected area to address unmet demand must be augmented by understanding the causes of unmet demand—that is, identifying bottlenecks, gaps, and broken links in local supply chains—and pursuing strategic interventions to assist local stakeholders in returning regular supply chains to normal operation as rapidly as possible.

2. **Build a system-level understanding of supply chain dynamics as a foundation for effective decision support.**

Supply chain management plays an important role in preparing for, responding to, and recovering from disasters—encompassing activities as diverse as developing early warning systems, pre-positioning and distributing relief supplies, evacuating affected populations, and managing storm debris (*2*). Supply chains rely on critical infrastructure such as power, communication, and transportation facilities (e.g., roads, airports, and ports)—all of which can be damaged and disrupted during a disaster.

The committee suggested key steps and strategies to advance this recommendation. For the given jurisdiction of concern (i.e., local, state, or regional), support pre-disaster assessment of the criticality, vulnerability, and dependencies of key supply chain nodes, links, and supporting infrastructure; and develop protocols and systems for gathering and regularly updating information about demand, supply, infrastructure condition, and supply chain functionality. Many private-sector supply chains already utilize sophisticated tools for sensing supply and demand changes, system bottlenecks and vulnerabilities, and other critical information. Public-sector officials need comparable capabilities and tools that can interface with—and build upon—these private-sector capabilities.

Emergency management offices at the local, state, and regional levels are likely best suited to lead much of this information collection and analysis work. However, FEMA can play a critical leadership role in building capacity and providing support for such efforts, through both financial incentives (i.e., grant programs) and training that brings together local knowledge with knowledge drawn from government and business leaders nationwide.

3. **Support mechanisms for coordination, information sharing, and preparedness among supply chain stakeholders.**

Opportunities for building resilience come from preparedness efforts undertaken before disasters strike. Examples of critical preparedness actions that businesses or organizations can take include developing and regularly updating emergency preparedness and continuity of operations

plans, conducting worst-case scenario drills, testing emergency communication protocols, and developing plans to protect organizational personnel during disaster events. Other critical factors for enabling successful disaster response are clearly defined processes and mechanisms for coordination and information sharing, especially platforms to engage across levels of government and public- and private-sector organizations.

There are many mechanisms for government agencies and responders at the local, state, and federal levels to interact with industry in responding to emergencies that affect supply chains. These include, for instance, the U.S. Department of Homeland Security's Critical Infrastructure Threat Information Sharing Framework and Homeland Security Information Network, the Information Sharing and Analysis Centers, and the Sectoral and Regional Consortium Coordinating Councils. Additional formal and informal mechanisms for coordination and information sharing, such as FEMA's National Business Emergency Operations Center, were utilized during the 2017 hurricane season.

Although each of these mechanisms can provide opportunities for coordination, ongoing consideration is needed to advance this collective "ecosystem" for engagement to minimize the time burdens placed on individual participants.

4. **Develop and administer training on supply chain dynamics and best practices for private–public partnerships that enhance supply chain resilience.**

Many engaged in emergency response have little or no experience working with private-sector entities or training for evaluating the impacts of a disaster on local supply chains and economics. University programs in emergency management and homeland security have few classes that provide the insights necessary to understand how disasters and emergency management strategies can affect supply chains and the economy as a whole.

To help stakeholders evaluate their decisions in a broader context, training should be provided to emergency managers and those supporting disaster operations (e.g., emergency operations center personnel, incident management teams, federal coordinating officers, and those in emergency support functions from other government agencies). Training could be provided through new courses in college emergency management programs; orientation training for new emergency managers, critical emergency operations center staff and stakeholders, and newly elected government officials; and FEMA's in-person and online training classes.

Training programs could enable participants to analyze factors such as economic drivers within their jurisdiction, data that can inform decisions about priorities for restoration assistance to supply chains, ways that supply chain disruptions can impact economic conditions, and the cost of disaster response or mitigation actions versus the costs of not taking those actions.

Conclusions

As FEMA's internal capacity and expertise on supply chain dynamics grow, the agency can play an increasingly valuable role assisting states, communities, the private sector, and other stakeholders with technical assistance and guidance. Although FEMA cannot be responsible for carrying out all of these activities, it can provide leadership for convening, coordinating, and empowering key partners.

This facilitating role should be proactive, going beyond grant programs to also provide jurisdictions with guidance for increasing understanding and capacity to implement new programs. Many state emergency management offices have significant capabilities but lack information access and sharing. They may have insufficient cooperation with other states, counties, and communities. With FEMA's experience and cross-jurisdictional scope, the agency could advise and guide state and local supply chain preparedness efforts across the country.

As weather disasters get costlier, more frequent, and affect more people, no single government agency can do everything to help communities prepare, respond, and recover. A whole community effort is required, involving federal, state, and local government agencies; the private sector; and nongovernmental organizations and civic groups, as well as individual households. FEMA's 2018 strategic plan highlights the goal of ensuring that communities have robust, adaptable supply chains that can withstand the stresses of extreme weather events. This goal is best attained by facilitating communitywide efforts to build systems and relationships that advance preparedness. The more advances that are made on these fronts, the less time, energy, and resources will be needed for emergency response and recovery.

The National Academies of Sciences, Engineering, and Medicine's Committee on Building Adaptable and Resilient Supply Chains After Hurricanes Harvey, Irma, and Maria was assembled by the Office of Special Projects in the Policy and Global Affairs (PGA) Division. The cornerstone activity of the PGA Office of Special Projects is the Resilient America program, which was established to implement recommendations from the 2012 National Academies report *Disaster Resilience: A National Imperative*. For the purposes of the accompanying article, resilience is defined as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events."

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