## 4.4 Consequence and Resilience Modeling for Chemical Supply Chains

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# Consequence and Resilience Modeling for Chemical Supply Chains

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The U.S. chemical sector produces more than 70,000 chemicals that are essential material inputs to critical infrastructure systems, such as the energy, public health, and food and agriculture sectors. Disruptions to the chemical sector can potentially cascade to other dependent sectors, resulting in serious national consequences. To address this concern, the U.S. Department of Homeland Security (DHS) tasked Sandia National Laboratories to develop a predictive consequence modeling and simulation capability for global chemical supply chains. This paper describes that capability, which includes a dynamic supply chain simulation platform called N-ABLE™. The paper also presents results from a case study that simulates the consequences of a Gulf Coast hurricane on selected segments of the U.S. chemical sector. The case study identified consequences that include impacted chemical facilities, cascading impacts to other parts of the chemical sector, and estimates of the lengths of chemical shortages and recovery. Overall, these simulation results can DHS prepare for and respond to actual disruptions.

## 1.0 INTRODUCTION

The U.S. Department of Homeland Security (DHS) [1] has identified that "protecting and ensuring the continuity of the critical infrastructure and key resources (CIKR) of the United States is essential to the Nation's security, public health and safety, economic vitality, and way of life." The chemical sector serves as one of the 18 CIKR sectors identified by DHS.

Analysis of chemical supply chains within this context is an inherently complex task, given the dependence of these supply chains on multiple CIKR systems (e.g., transportation, energy). This effort requires data and information at various levels of resolution, ranging from network-level supply chain systems to individual chemical reactions.

DHS has tasked the National Infrastructure Simulation and Analysis Center (NISAC) with development of a chemical infrastructure analytical capability to assess interdependencies and complexities of the nation's critical infrastructure, including the chemical sector. The Federal Government established NISAC, which includes personnel at Sandia National Laboratories (Sandia) and Los Alamos National Laboratory to support efforts aimed at identification of dependencies within and across sectors, providing consequence assessment to enable National Risk Analysis.

To address this need, DHS's Science and Technology Directorate has funded the Sandia component of NISAC in an ongoing effort to integrate its existing simulation and infrastructure analysis capabilities with various chemical industry datasets. The intent of this effort is to develop and ultimately provide capabilities in consequence and resilience analysis of natural and manmade events that impact the chemical industry and chemical-dependent sectors of the economy.

This document describes key elements of this ongoing development effort, including the modeling and simulation tools utilized in analyzing the chemicals sector from different perspectives. This includes a case study, examining the effects of a Gulf Coast hurricane on segments of the chemicals sector and an examination of consequence and resilience metrics.

## 2.0 BODY

Consequence and resilience analysis of the chemicals sector requires a wide range of modeling techniques to answer questions of varying scopes, acting on a common data set. To do this, Sandia developed and populated a common data model, a set of modeling capabilities with different resolutions, and a framework for analyzing resilience.

## 2.1 Chemical Data Model (CDM)

Central to the development effort aimed at providing consequence and resilience analysis is a common Chemical Data Model (CDM). The CDM draws on infrastructure, population, labor, economic and other data sets from a variety of commercial (e.g., SRI Consulting, PennWell, Minnesota IMPLAN Group) and government (e.g., U.S. Bureau of the Census, National Geospatial-Intelligence Agency, and Surface Transportation Board) data sources, as well as on data developed during the project. CDM data are updated annually, at minimum, or as often as updates become available.

Figure 1 represents a simplified schematic of how the information within CDM is organized, merged, and stored. Each chemical plant in the database has attributes that identify where it is located, what chemicals are produced and stored, the associated capacities for production and storage, and what production technologies are used at the plant.

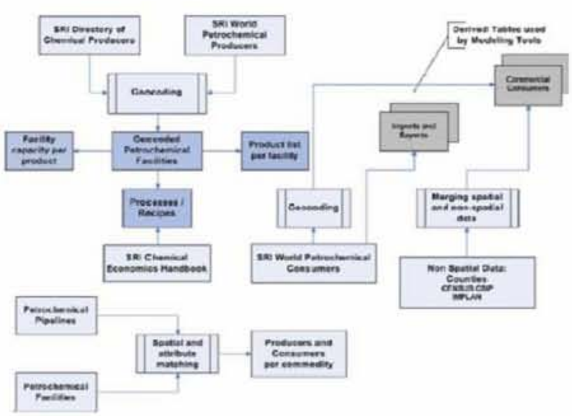


**Figure 1. The Chemical Data Model.**

## 2.2 Consequence Analysis Tools

A variety of Sandia-developed tools leverage this common data structure for various aspects of analysis of the chemicals sector (and other sectors as appropriate to the question).

### 2.2.1 FASTMap

Geospatial analysis is conducted using a tool called FASTMap. FASTMap is a geographic information system (GIS)-based tool that creates common look-and-feel, production-quality maps of the chemicals sector and other CIKR sectors relative to disruption areas, and provides data on CIKR assets (e.g., names, number of facilities) in the disruption area.

### 2.2.2 Fast Analysis Infrastructure Tool (FAIT)

Infrastructure dependency analysis is conducted within a tool called the Fast Analysis Infrastructure Tool (FAIT). FAIT provides data on the dependencies of specific chemical sector components (e.g., plants and pipelines) on assets in other infrastructure (e.g., electric power, transportation, emergency services).

### 2.2.3 Loki

Network analysis is conducted using a tool called Loki, which is a network model and analysis tool designed to quickly estimate potential production losses among chemical manufacturing processes.

### 2.2.4 Railroad-Network Analysis System (R-NAS)

Rail transportation analysis is accomplished through a network tool called the Railroad-Network Analysis System (R-NAS). R-NAS models the U.S. national rail network and estimates the impact to national rail commodity flows given disruptions to the rail system (bridges, rail yards, and so forth).

### 2.2.5 NISAC Agent-Based Laboratory for Economics (N-ABLE™)

Dynamic supply chain analysis is conducted using the NISAC Agent-Based Laboratory for Economics™ (N-ABLE™), a large-scale microeconomic supply chain model and tool that allows for the analysis of the impacts to individual firms (production, sales, transportation, and inventories) and the broader supply chain over time (output, shipments, and inventories) resulting from disruptions to firms and transportation networks [2], [3]. N-ABLE™ draws on the results of the other analysis tools and subject matter expertise to define disruption parameters and simulate individual firm behaviors within the modeled supply chains. Figure 2 shows a representation of the interaction of a typical N-ABLE™ enterprise firm, containing different types of decision makers with objectives, interaction with each other, with supporting CIKR, and with upstream and downstream 'markets' for input commodities and output products. Entire supply chains are constructed from collections of firms, based on this enterprise design, with each participating firm interacting with others through markets and physical infrastructure.

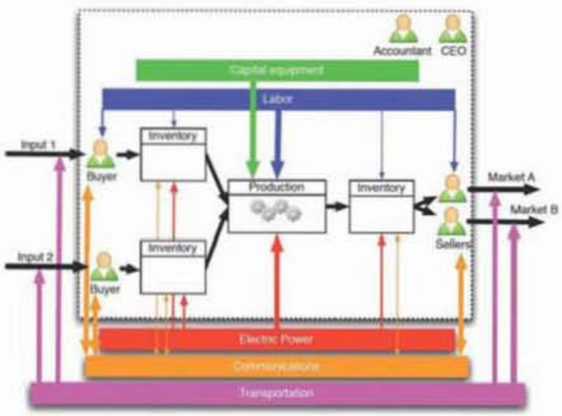


**Figure 2. N-ABLE™ Enterprise Model of an Economic Firm.**

N-ABLE™ simulation results provide quantitative and qualitative information necessary for consequence analyses. For example, if a hurricane temporarily shuts down a set of chemical production facilities, N-ABLE™ estimates economic impacts resulting from a decreased chemical supply to downstream facilities (e.g., customers of the closed facilities, the customers of the customers, etc.). N-ABLE™ also estimates losses resulting from a decreased demand of input chemicals used by the closed production plants to upstream facilities (e.g., suppliers to the closed plants, suppliers of the suppliers, etc.). These economic impact and loss estimates can be used to measure the systemic impacts to the chemical supply chain from a hurricane.

In addition, N-ABLE™ estimates the time necessary for the system to recover from a disruption. In the case of chemical supply chains, supply interruptions can cascade through many other sectors at different rates. Some downstream consumers will feel the impact of interrupted production immediately, some will not feel the impact until days or weeks later, and some will not feel it at all. Inherent in N-ABLE™ is the capability to represent the search for other supply sources when losses occur and any changes in transportation costs associated with the need to use alternate suppliers. The cost estimates associated with the recovery and adaptation processes are crucial to estimating supply chain recovery processes.

### 2.3 Resilience Analysis Framework

A uniform, methodical approach for assessing resilience of infrastructure systems is required to successfully incorporate resilience into critical infrastructure protection (CIP) policies and business planning practices. This approach needs to be general enough to apply to all types of infrastructure systems to account for dependencies between different infrastructure types and establish standards across all infrastructure types. Furthermore, resilience assessment approaches should explicitly account for the costs of recovery processes in comprehensive disruption cost evaluations.

With these two requirements in mind, Sandia has developed a novel framework for evaluating the resilience of infrastructure and economic systems [4]. The framework includes a new definition of resilience, a mathematical resilience cost measurement approach, and a qualitative analysis methodology that assesses system characteristics that affect resilience. This framework can be applied to studies of natural and manmade disruptions.

The framework as developed presents a mathematical resilience cost measurement approach that can be used to objectively determine the impacts of disruptions on a system and the resilience costs associated with disruptions. The resilience cost measurement approach requires quantification of two key components of the definition of system resilience: systemic impact (*SI*) and total recovery effort (*TRE*). *SI* is the impact that a disruption has on system productivity and is measured by evaluating the difference between a targeted system performance (*TSP*) level and the actual system performance (*SP*) following the disruption. *TRE* refers to the efficiency with which the system recovers from a disruption and is measured by analyzing the amount of resources expended during the recovery process. The measurement of system resilience costs requires the quantification of both *SI* and *TRE*.

Figure 3 graphically represents systemic impact for a hypothetical system that has been disrupted. In this example, system performance decreases immediately following the disruption shock. With the onset of recovery actions, performance levels eventually increase and ultimately attain targeted system performance levels. At this point, recovery is considered complete. *SI* is quantified by calculating the area between the *TSP* and the actual *SP* curves in Fig. 3. This area is calculated using the formula in Eq. (1).

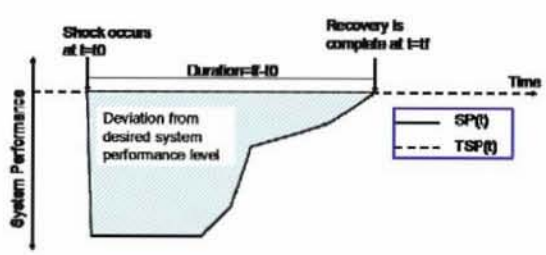


**Figure 3. Systemic Impact (SI).**

$$SI = \int_{t_0}^{t_f} [TSP(t) - SP(t)]\, dt \qquad \text{Eq. (1).}$$

Figure 4 illustrates the recovery response for the system shown in Fig. 3. After the disruption initiates, the recovery response begins and resources are expended in this effort. The *TRE* is the cumulative amount of resources expended during the recovery period and is represented by the area under the recovery effort (*RE*) curve in Fig. 4. This area is calculated by Eq. (2).

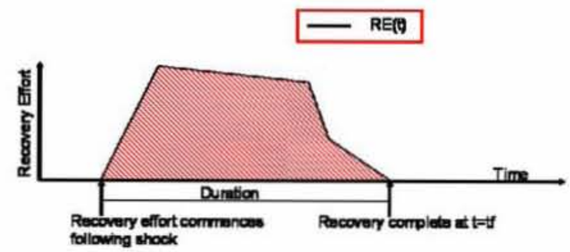


**Figure 4. Total Recovery Effort (TRE).**

$$TRE = \int_{t_0}^{t_f} [RE(t)]dt \qquad \text{Eq. (2).}$$

System performance is determined by the *RE*. That is, different *RE*s lead to different system performances. For example, if no *RE* is made following the disruption, the loss of system performance may be great. In contrast, if recovery resources are deployed shortly after the system shock, system performance may not be significantly affected, and *SI* may be small. The recognition that *SI* is implicitly determined by the selected recovery strategy leads to the development of recovery-dependent resilience (*RDR*) cost measurements. *RDR* costs are the resilience costs of a system under a particular recovery strategy and are calculated with Eq. (3).

$$RDR(RE) = \frac{SI + (\alpha \times TRE)}{\int_{t_0}^{t_f} |TSP(t)| dt} \qquad \text{Eq. (3).}$$

*RDR* costs are linear combinations of SI and *TRE*. The denominators in Eq. (3) are normalization factors that permit the comparison of the resilience of systems of different magnitudes. Because resilience represents a balancing of *SI* and *TRE* costs, the calculation of *RDR* costs includes the parameter α, which is a weighting factor that allows an analyst to assign the relative importance of the systemic impact and total recovery effort terms. Assigning a small positive value to α weighs the systemic impact more heavily; a large positive value for α weighs the cost of recovery more heavily. To equally weigh *SI* and *TRE*, α is set to 1.

In addition to RDR costs, optimal resilience (*OR*) costs can also be considered, but their calculation is beyond the scope of this work at present.

When applied to the CDM, N-ABLE™ simulations can provide quantitative and qualitative information necessary for resilience analyses. For example, if a hurricane temporarily shuts down a set of chemical production facilities, N-ABLE™ can estimate economic impacts resulting from a decreased chemical supply to downstream facilities (e.g., customers of the closed facilities, the customers of the customers, etc.). N-ABLE™ can also predict losses resulting from decreased demand of input chemicals used by the closed production plants to upstream facilities (e.g., suppliers to the closed plants, suppliers of the suppliers, etc.). These economic impact and loss estimates can be used to measure the *SI*s to the chemical supply chain from a hurricane.

In addition, N-ABLE™ can predict how the chemical sector will adapt to and recover from a disruption. The tool has the capability to estimate production curtailments by the customers of the closed plants that cannot find new suppliers, the higher transportation costs associated with new suppliers, the use of chemical substitutes, and the implementation of different production technologies and recipes to adapt to a disruption. The cost estimates associated with the recovery and adaptation processes are crucial to calculating the *TRE* in a resilience analysis.

## 3.0 DISCUSSION

### 3.1 Analysis Basis

The methodology, models, data, and other capabilities described above have been applied to a variety of homeland security problems. The following summary of an analysis of a Category 3 hurricane making landfall in the Gulf Coast is an example of this application.

The scenario hurricane was patterned after the actual Hurricane Ike (2008), which developed during the early part of September and made its landfall over coastal Texas on September 13, 2008. The storm moved at a projected forward speed of 12 miles per hour (mph), carrying maximum sustained winds of over 100 mph. The storm size was approximately 230 miles, and it was the third most destructive hurricane in U.S. history. Figure 5 shows the projected path of Hurricane Ike early on September 11, 2008.


**Figure 5. Projected Path of Hurricane Ike, NOAA Advisory 41, 0400 CDT September 11, 2008.**

Sandia used the scenario storm parameters (trajectory and category) in this analysis to first estimate the damages from wind and surge waters. These damage estimates are translated into areas of probable electric power outage and inland flooding depths. Sandia analysts then assessed potential direct impacts to chemical facilities, petroleum refineries, and the natural gas network for elements physically affected by this scenario storm. Analysts then assessed the indirect impacts to facilities and infrastructures not in the path of the hurricane but dependent on facilities within the disruption area. Finally, analysts estimated cascading impacts to the chemical industry and petrochemical supply chain at a regional, national, and global level. Figure 6 shows the estimated electric power disruption area for the scenario hurricane. Differences in color reflect the likelihood of power outage (green reflecting a 0- to 25-percent probability of outage, red representing a 75- to 100-percent probability of power outage), while intensity of color reflects the projected duration of disruption (lighter shades representing shorter duration of outage where present, darker shades representing longer duration of outage where present).

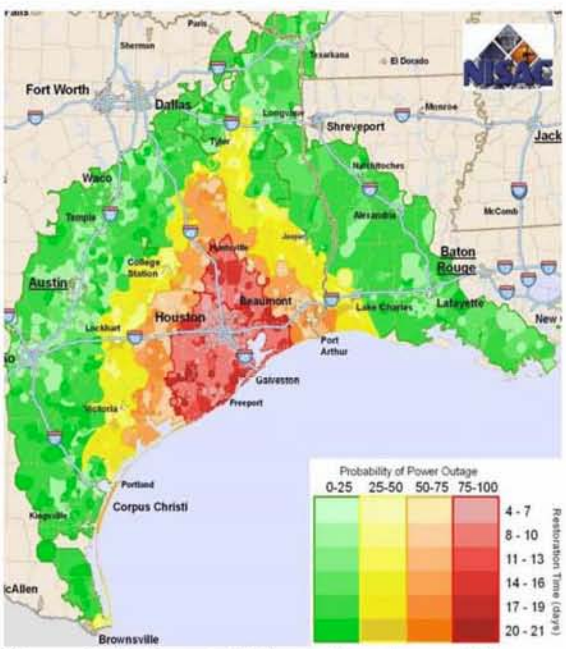


**Figure 6. Estimated Disruption Area of the Scenario Hurricane.**

It is common practice for Gulf Coast petrochemical production facilities in the projected path of a hurricane to shut down operations 48 hours prior to hurricane landfall. On average, the petrochemical facilities within the electric power outage contours will be without power for a few weeks. Production at these facilities will not likely be restored immediately following restoration of power. Following a plant shutdown, petrochemical facilities often require additional startup time to perform system checks, such as purging pipelines and vessels with inert gases such as nitrogen, to ensure the unit's operability. To simulate the cumulative effects of these, analysts assumed that all petrochemical facilities within the outage contours are shut down for 25 days.

To quantitatively evaluate the resilience of the petrochemical supply chain, we ran two sets of N-ABLE™ simulations. In the baseline scenario, we assumed no disruptions. In the disruption scenario, we assumed that a hurricane is projected to make landfall on day 202 of the simulation and the electric power outage shown in Figure 6 is expected to occur. On day 200, all petrochemical facilities within the contours shut down in anticipation of the storm. Normal production capabilities are assumed to return on day 225 of the simulation.

The market value of production (*MVP*) is the metric used to measure *SI*. *MVP* captures total "street value" of every step of chemical-unit production. It is similar to the sale value of end products, but it counts production at every stage in the production process, whereas the sale value only counts chemicals that are sold on the merchant market. *MVP* equals sale value of end products if there is absolutely no vertical integration, i.e., outputs of every stage of the production process are sold on the merchant market

For this analysis, two factors are considered in determining *TRE*: additional aggregate transportation costs (*TC*) and production plant shutdown/restart costs (*RC*). When a disruption decreases the supply of available chemicals, consumers of those chemicals will seek new suppliers. These suppliers will likely be farther from the consumers than the original suppliers, so the cost of transporting chemicals from the new suppliers will likely be greater due to the increased transportation distances

Cost engineering estimates RCs as a percentage of the capital costs of the equipment involved. Pre-planned, short-term shutdowns are generally less expensive, based on available data. After literature review, consultation with project subject matter experts and economists at the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) and the American Chemistry Council (ACC), the authors utilized an *RC* of 3 percent of capital costs.

For the sake of simplicity, we only consider the *TC*s and *RC*s when calculating the *TRE* for this example. To calculate *RDR* costs, we set α to 1 in Eq. (3) and approximate the integral with 1-day time-step intervals because N-ABLE™ reports data on a daily basis.

Figure 7 shows *MVP* as a function of time for the base case and the scenario hurricane for the whole Ethylene supply chain. Utilization of inventories (in hand and in transit) helps to buffer some of the effects of the disruption.

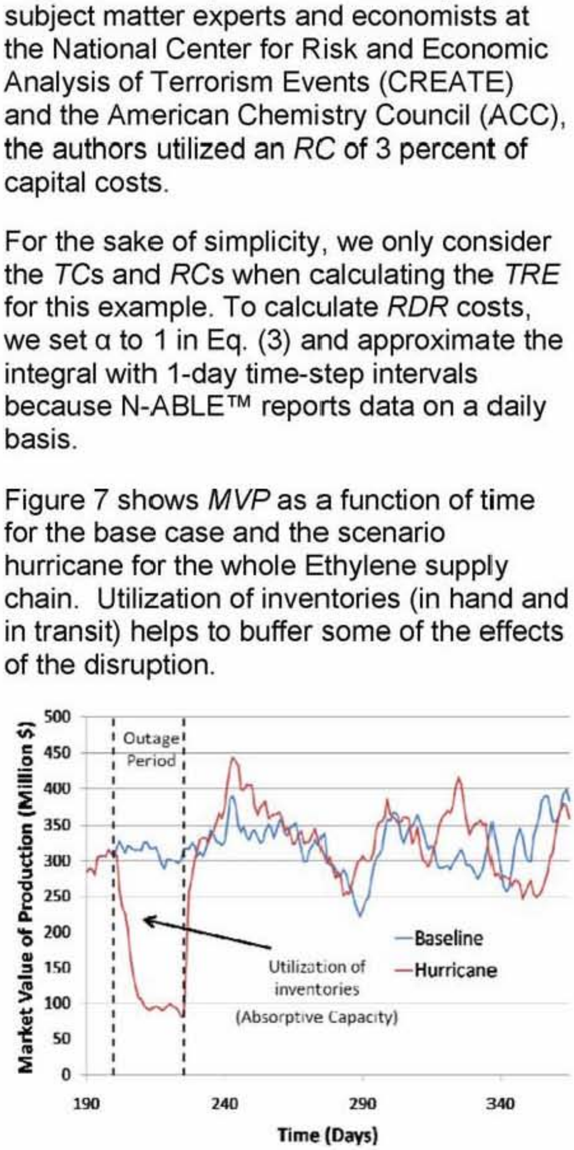


**Figure 7. *MVP* as a function of time, Ethylene Supply Chain, Base and Hurricane Scenarios.**

Figure 8 shows average shipment distance as a function of time for the base case and the scenario hurricane for the whole Ethylene supply chain. The inventory utilization described in Figure 7 comes at a cost, which reflects through in the calculation of *TC*, and as a result, on *TRE*.

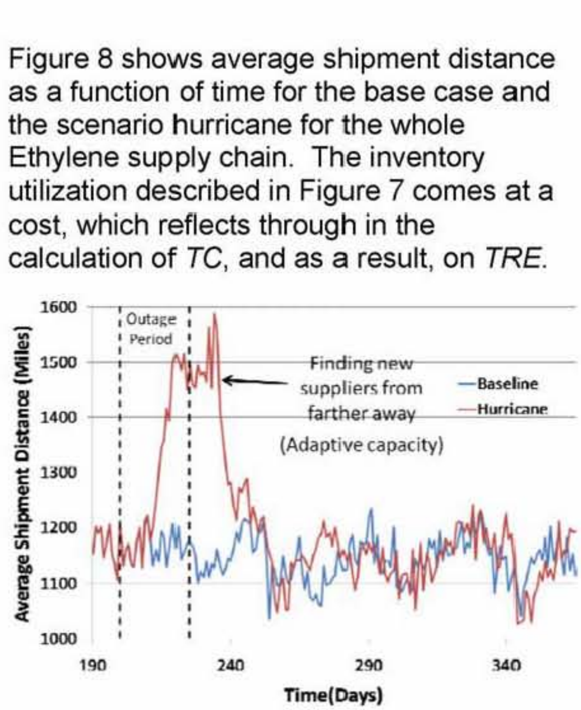


**Figure 8. Average Shipment Distance as a Function of Time, Ethylene Supply Chain, Base and Hurricane Scenarios.**

Table 1 shows the comparative analysis of the calculation of System Resilience for the whole Ethylene supply chain and for a segment, Vinyl acetate monomer (VAM). Impacts to VAM production are more severe than the aggregate, transportation distances and costs greater, and recovery period longer. As such, the VAM resilience metric is larger by one-third than that of the Ethylene supply chain as a whole (here, a lower value reflects a more resilient system).

**Table 1. Comparison of Resilience Values, Hurricane Scenario, VAM and Ethylene Supply Chains**

| Measure | VAM | Ethylene |
|---|---|---|
| Target *MVP* ($M) | 856 | 49,000 |
| *SI* ($M) | 88 | 4,000 |
| *TRE: RC* ($M) | 11 | 256 |
| *TRE: TC* ($M) | 1.5 | 254 |
| Resilience | .12 | .09 |
| Resilience = (*SI* + (*RC* + *TRE*))/Target *MVP* | | |

A more detailed discussion of the consequence and resilience analysis results for this scenario will be presented at MODSIM World 2010.

## 4.0 CONCLUSION

Analysis of chemical supply chains is an inherently complex task, given the dependence of these supply chains on multiple infrastructure systems (e.g. transportation and energy). The capability developed at Sandia is intended to provide information to the DHS with respect to the consequences of large-scale disruptions to the chemical sector, including interrupted supply and resulting economic impacts to the nation, which can be utilized to inform response and recovery officials, enabling more effective pre-event planning and more knowledgeable event response. The ongoing development effort includes the development of several tools along with a comprehensive database that feeds the tools. The database is constructed by merging many datasets in combination to provide a high degree of resolution within the data so that individual plants can be uniquely represented.

The hurricane disruption scenario presented herein shows that large-scale disruptions to petrochemical supply chain elements affect many supply chains and, consequently, take considerable time to recover (Figures 7 and 8). Supporting this result in the scenario analysis, information reported in Chemical Week showed that

> Several Texas Gulf Coast chemical plants began to restart operations after shutting down ahead of Hurricane Ike's landfall on September 13, 2008. However, producers claim that the ready availability of utilities, raw materials, and logistics, and the damage at some customer sites negatively affect their effort to restart operations [5].

The disruption to chemical plants cascade both up and down the supply chain, affecting recovery efforts.

## 5.0 REFERENCES

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## 6.0 ACKNOWLEDGMENTS

The authors would like to thank John Masciantoni for providing N-ABLE™ assistance.

The authors would like to thank Adam Rose and Tony Barrett from the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) for their thoughtful insights on this work.

The authors performed this work with funding from the U.S. Department of Homeland Security's Science and Technology Directorate.

Sandia is a multiprogram laboratory operated by Sandia Corporation for the Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

2010-6509C



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Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



## Acknowledgements

- The authors performed this work with funding from the U.S. Department of Homeland Security's Science and Technology Directorate.

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## Outline

- Introduction
- Technical Elements
  - Chemical data model (CDM)
  - Consequence Analysis Tools
  - Resilience Analysis Framework
- Measuring Resilience
- Summary
- Questions

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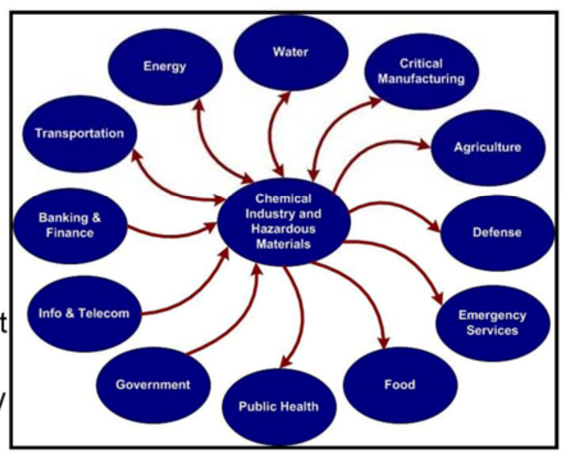
## Introduction

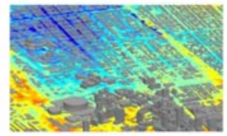
- Chemical sector is highly connected to multiple infrastructures and commercial sectors
- Consequence analysis capability must consider
  - Disruptions of the chemical sector
  - Disruptions of interdependent infrastructures
  - National, regional, and facility perspectives



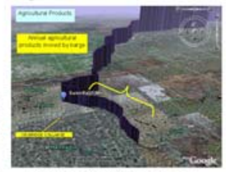
## Introduction

### Supply chains face an array of threats

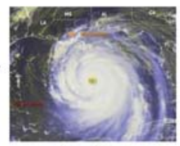
- "Protection, in isolation, is a brittle strategy"
- Effective integration of resilience into critical infrastructure protection policies requires
  - Consistent, broadly applicable definitions and methods
  - Objective methods for measuring progress
  - Comprehensive accounting of resource-constrained recovery strategies



*Flooding*



*Commodity Flow Impacts*



*Hurricane*

"We are working every day to ensure our country stands ready to respond to any disaster or emergency -- from wildfires and hurricanes, to terrorist attacks and pandemic disease. Our goal is to ensure a more *resilient* Nation."
–President Barack Obama, September 4, 2009

## Introduction

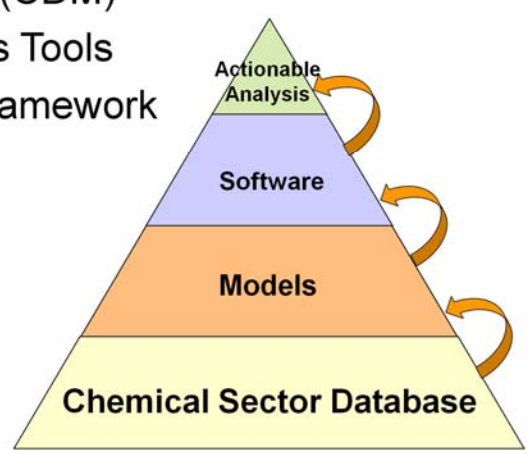
- We need to address direct impact questions
  - What is the area of direct impact?
  - What chemical facilities are directly affected?
  - What percentage of capacity does this represent?
- And cascading impact questions
  - How long before we return to 'normal'?
  - What additional facilities will be affected?
- We also need to be able to examine systemic resilience
  - Define
  - Calculate

# Introduction

| Organization | Role |
|---|---|
| DHS Science and Technology (S&T) Directorate, Infrastructure and Geophysical Division | Manage the chemical supply chain and resilience project |
| Sandia National Laboratories, Interdependencies and Consequence Management Group | Develop analysis and design capabilities |
| National Infrastructure Simulation and Analysis Center (NISAC) (managed by DHS Office of Infrastructure Protection [IP]) | Apply completed capabilities to disruptions of critical infrastructures and key resources (CIKRs) |

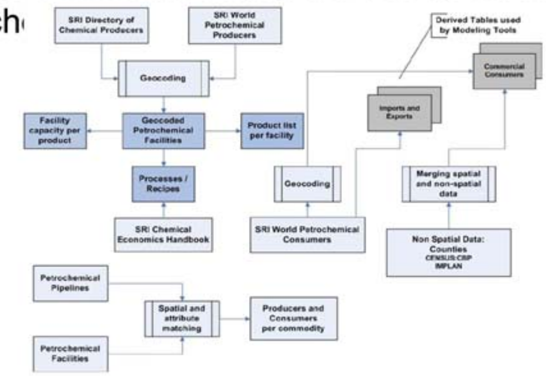
# Technical Elements

- Chemical Data Model (CDM)
- Consequence Analysis Tools
- Resilience Analysis Framework



## Technical Elements: CDM

- Data foundation for the project
  - All models are driven from the same set of core input data
  - Differences in model output are due to modeling approach




## Technical Elements: CDM

- Project models and analysis tools need the following information
  - Plant facilities
    - Name
    - Location (address and geocodes)
  - Facility productions
    - Chemical types
    - Quantities
    - Processes
  - Infrastructure dependencies
    - Transportation (rail, pipeline, etc.)
    - Energy (electric power, natural gas, petroleum products)
    - Quantities
  - Consumption
    - Categories
    - Locations
    - Quantities
  - Imports/exports
    - Locations
    - Quantities
  - Other factors
    - Economics
    - Population distribution
    - Emergency services

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## Technical Elements: CDM

| Dataset Name | Provider |
|---|---|
| World Petrochemicals Program 2009 | SRI Consulting |
| Chemical Economics Handbook 2009 | SRI Consulting |
| Directory of Chemical Producers 2009 | SRI Consulting |
| Oil & Gas Pipelines | NGA HSIP Gold 2008 (PennWell) |
| Oil & Gas Facilities | NGA HSIP Gold 2008 (PennWell) |
| United States Census 2000 | U.S. Census Bureau |
| County Business Patterns 2007 | U.S. Census Bureau |
| County Business Patterns Employees Estimation 2007 | U.S. Census Bureau |

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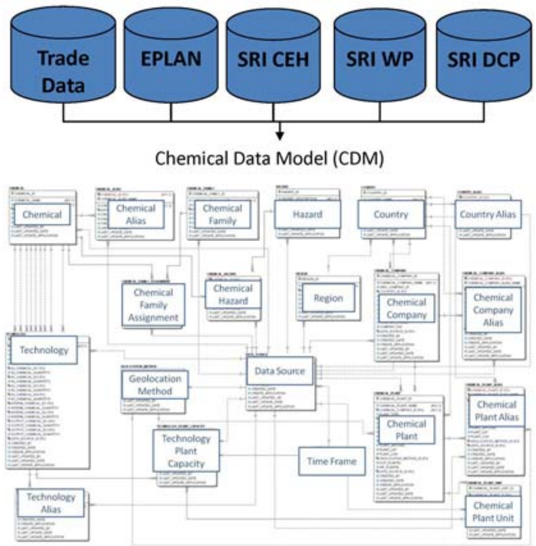
## Technical Elements: CDM

| Dataset Name | Provider |
|---|---|
| Geographic Names Information System | U.S. Geological Survey |
| IMPLAN States Summary 2002 | Minnesota IMPLAN Group |
| International Trade Statistics 2007 | U.S. Department of Commerce |
| Refinery Location Data | Argonne National Laboratory* |
| 2005 Commodity Flow Survey, Department of Transportation | 2005 Waybill Sample, Surface Transportation Board |
| 2007 Class I Railroad Statistics, Association of American Railroads | 2007 Producer Price Index, Department of Labor |
| E-Plan Emergency Response Information System | U.S. Environmental Protection Agency/U.S. Department of Homeland Security |

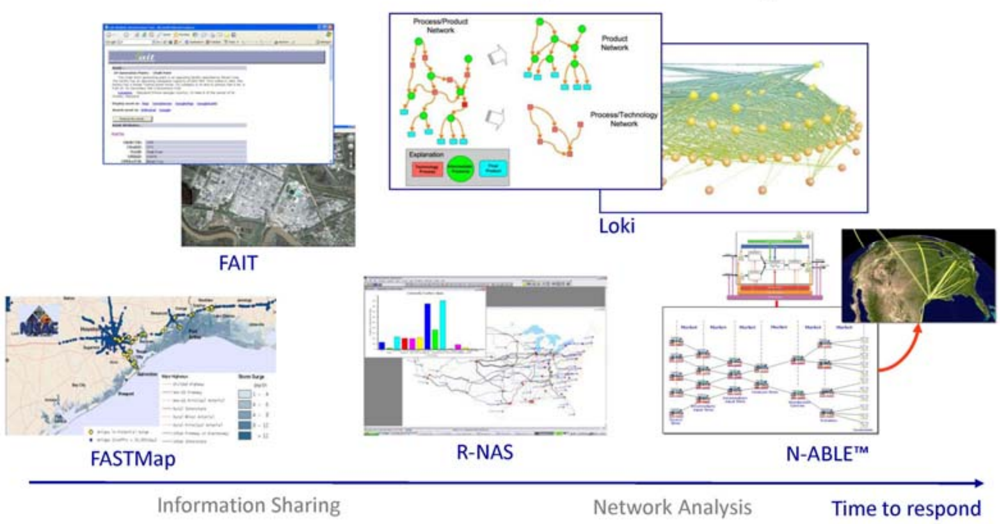
* Argonne data were updated using 2007 domestic data from the Energy Information Administration (EIA) and foreign data from SRI Consulting.

## Technical Elements: CDM

- CDM Building Process
  - Gather
  - Process and integrate
    - Merge datasets into a common, Oracle-based framework
  - Authenticate
  - Document
  - Ensure traceability
  - Test
    - Ensure compatibility with models
  - Iterate

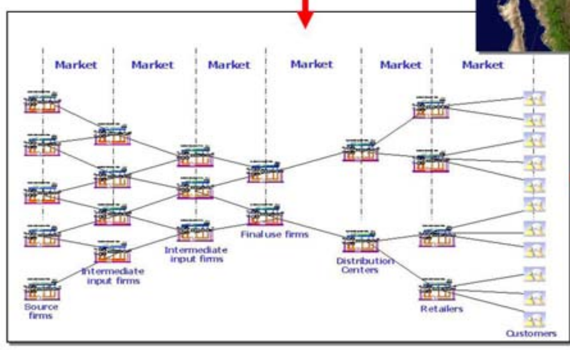



## Technical Elements: Consequence Analysis Tools



## Dynamic Supply Chain Analysis with the NISAC Agent-Based Laboratory for Economics (N-ABLE™)

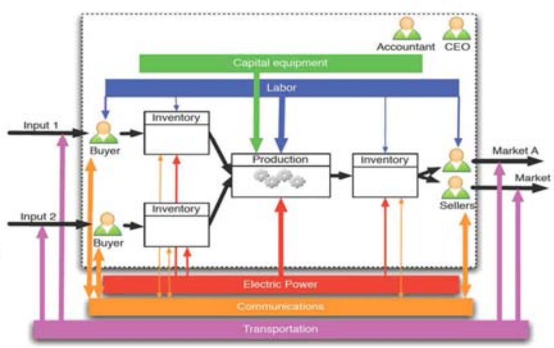
Individual enterprises are combined to create networks of enterprises




The networks of enterprises comprise national, regional, and local markets

## Model Foundation of N-ABLE™: The Enterprise Firm

- N-ABLE™
  - Generates data-driven microeconomic "enterprises"
  - Simulates enterprise operations (buyers, production, sellers, inventories, and shipping)
  - Identifies interactions in markets and dependencies on critical infrastructures
  - Estimates how enterprises respond individually and collectively to disruptions



## Resilience Framework: A Definition of Resilience

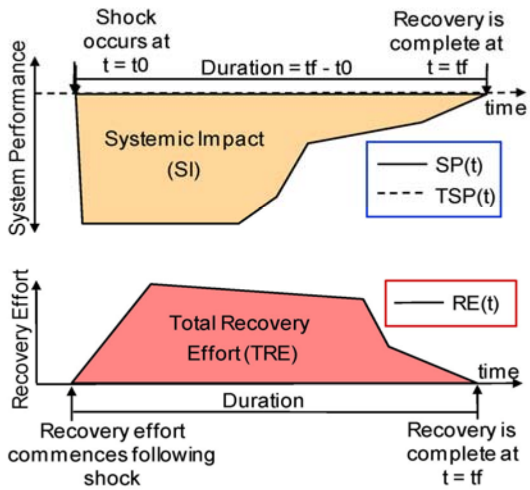
- Resilience is contextual
  - Relative to disruptive event and performance targets
- System performance is a fundamental factor
  - Structure not as important as performance
  - We consider magnitude and duration
  - We do not assume a system will return to pre-disruption state
- Resource expenditure in recovery processes a fundamental consideration
  - We consider the ability to efficiently reduce system impacts to absorb, adapt, and/or recover

## Resilience Framework: A Definition of Resilience

"Given the occurrence of a particular, disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels."

-Vugrin et al., 2010

## Resilience Framework: Calculation of Resilience Costs




$$\text{Resilience Costs} = \frac{SI + \alpha \times TRE}{\int_{t0}^{tf} |TSP(t)| dt}$$

## Resilience Framework: Qualitative Resilience Assessment

Resilience = Systemic Impact + Total Recovery Effort

| Component | Systemic Impact | | Total Recovery Effort |
|---|---|---|---|
| Determining Features | Absorptive Capacity | Adaptive Capacity | Restorative Capacity |
| Distinguishing Characteristics of Capacity | Considers aspects that automatically manifest after the disruption | Considers internal aspects that manifest over time after the disruption | Considers ability to affect and repair internal system features |
| Effort Required | Automatic/ Little Effort | Internal Effort Required | External Effort Often Required |
| Measurement of Component | Internal Measurement | | Exogenous Measurement |

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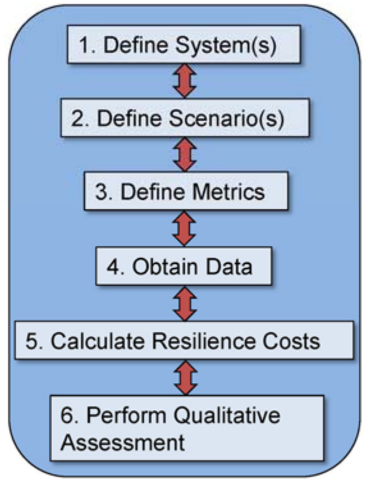
## Resilience Framework: Resilience Analysis Process

- To apply the conceptual framework to the chemical sector, we must define several key components of the analysis process, such as
  - Chemicals under consideration
  - Performance metric
- We require subject matter expertise for this process
- We will demonstrate the resilience analysis process for a scenario hurricane

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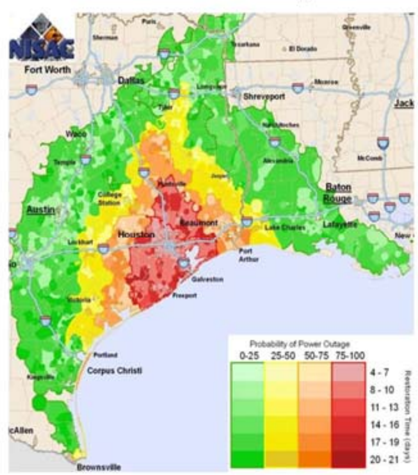
## Measuring Resilience: Scenario Assumptions

- Hurricane makes landfall and affects plants in electric power (EP) outage contours
- Facilities within the outage contours shut down 2 days prior to landfall
- These facilities are nonoperational for an additional 23 days
- All facilities that are within outage contours require startup processes




Estimated Power Outages & Restoration Times

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## Measuring Resilience: Defining Metrics

- Market value of production (MVP)
  - Total "street value" of every step of production for all chemicals and facilities

$$MVP(t) = \sum_i \sum_j Q_{i,j}\ \ t\ \times p_i$$

Chemical price per unit mass ($p_i$)

Mass produced of chemical ($Q_{i,j}$)

  - Systemic impact metric = MVP for disrupted conditions
  - Targeted system performance = MVP for undisrupted conditions

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## Measuring Resilience: Defining Metrics (continued)

- Total recovery effort metric 1:
  - Additional transportation costs (TC) due to increased transport distances

$$TC(t) = \left[ \sum_i MD\ \ i,t\ \right] \times \left[ D_{ave}^{D}\ \ t\ - D_{ave}^{B}\ \ t\ \right] \times C_{car} \times C_{\cos t}$$

Increased average distance/shipment

$3/car-mile

Met demand for a chemical (short tons)

(1 car /100 short tons)

## Measuring Resilience: Defining Metrics (continued)

- Total recovery effort metric 2:
  - Production plant shutdown/restart costs: cost engineering estimates these cost as a percent of capital costs
  - Pre-planned, short-term shutdown is generally less expensive
  - After consultation with project chemical subject matter expert, literature, and economists at National Center for Risk and Economic Analysis of Terrorism Events (CREATE) and American Chemistry Council (ACC), we use <u>3 percent of capital costs to estimate shutdown/restart costs</u>

$$RC = 0.03 \times \sum_j CC_j$$

Capital cost per plant

Restart Costs as a Percent of Capital Costs

| Source | Range | Median |
|---|---|---|
| Perry (2008) | - | 3% |
| Peters and Timmerhaus (1968) | 0.5-2% | 1.3% |
| Peters and Timmerhaus (1980) | 8-10% | - |
| Price (2009) | 5-20+% | - |

## Measuring Resilience: Calculation of Resilience Costs

- Recall that

$$\text{Resilience Costs} = \frac{\text{System Impact} + \alpha \times \text{Total Recovery Effort}}{\text{Targeted System Performance}}$$

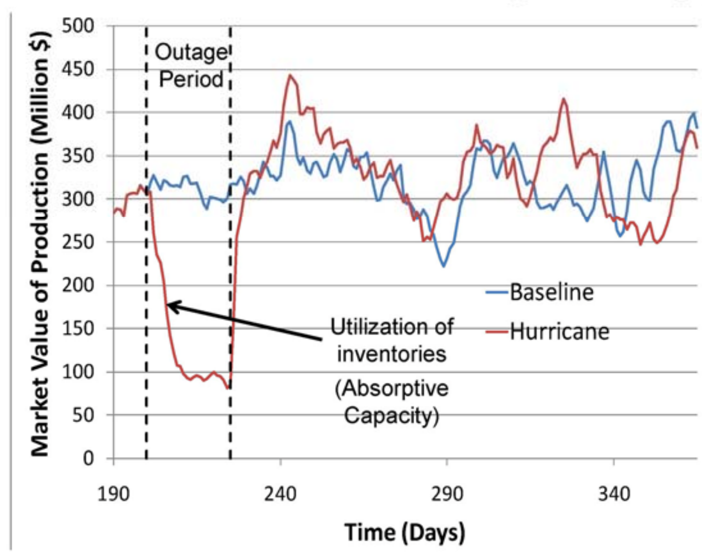
- Therefore, for this analysis:

$$RC = \frac{MVP_{Baseline} - MVP_{Disrupted} \;+\; TC + RSC}{MVP_{Baseline}}$$

## Measuring Resilience: Obtaining Data through N-ABLE™ Simulations

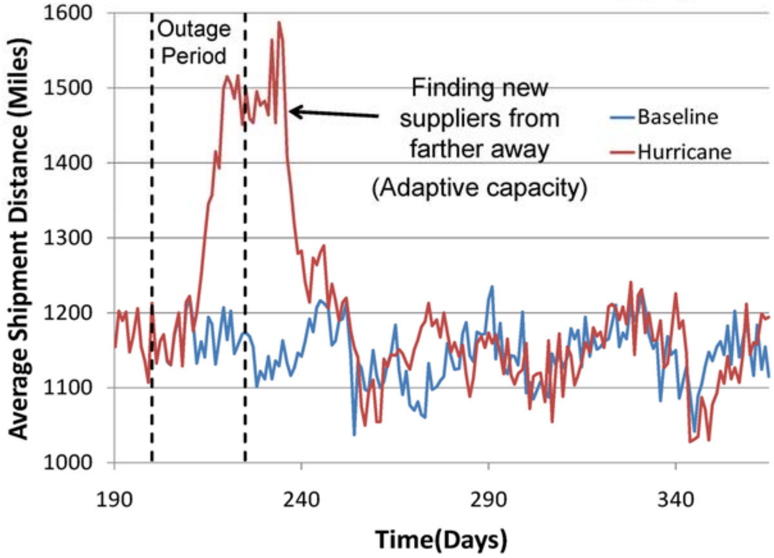
- Two sets of N-ABLE™ 1-year simulations were executed
  - Baseline and disrupted conditions
- In the disrupted simulation
  - Plant shutdown is assumed to occur on day 200, and
  - Affected plants are assumed to be fully operational on day 225
- Simulations provide MVP and TC data
- Restart costs (RC) are estimated external to the simulation

## Measuring Resilience: Systemic Impact, Whole Ethylene Supply Chain




When is recovery complete?

## Measuring Resilience: Adaptive Behaviors, Whole Ethylene Supply Chain




## Measuring Resilience: Calculating Resilience Costs

| Measure | VAM | PVC Chain | Entire Chain |
|---|---|---|---|
| Recovery "Complete" on Day | 264 | 260 | 250 |
| Target MVP ($M) | 856 | 14,800 | 49,000 |
| Systemic Impact ($M) | 88 | 1,100 | 4,000 |
| Recovery Effort: Restart ($M) | 11 | 23 | 256 |
| Recovery Effort: Transportation ($M) | 1.5 | 9.6 | 254 |
| Resilience Cost | .12 | .08 | .09 |
| *Resilience Cost = (Systemic Impact + Total Recovery Effort)/Target MVP* | | | |

## Measuring Resilience: Calculating Resilience Costs

- Systemic impact dominates recovery costs in all systems
- Restart costs far outweigh increased transportation costs
- Restart and transportation costs for VAM are relatively high
- Though the VAM system is the smallest, it is also the least resilient
  - Simplicity may hinder resilience

## Summary

- This project takes a multidisciplinary approach to chemical supply chain modeling and resilience analysis
- We have integrated our consequence analysis capabilities into a resilience framework to enhance analytic capabilities
- We plan to continue capability development efforts this year
- We welcome, encourage, and value feedback

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## Acknowledgements

- The authors would like to thank John Masciantoni for providing N-ABLE™ assistance.
- The authors would like to thank Adam Rose and Tony Barrett from the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) for their thoughtful insights on this work.

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## Questions?