An Operational Model of the Critical Supply Chain for the U.S. Virgin Islands

M.S. Thesis in Operations Research (Sept. 2019, expected), Naval Postgraduate School, Monterey, CA

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FEMA

U.S. DEPARTMENT OF ENERGY

NAVAL POSTGRADUATE SCHOOL

University of the Virgin Islands
Territory Characteristics

Florida ~1,100 Miles

Puerto Rico ~40 Miles
Territory Characteristics

Florida → Puerto Rico

Distance:
- Florida to Puerto Rico: ≈ 1,100 miles
- Puerto Rico: ≈ 40 miles
Territory Characteristics

Florida (FL) → Puerto Rico (PR) → St. Thomas (STT)

Florida ~1,100 Miles
Puerto Rico ~40 Miles

St. Thomas
Territory Characteristics

FL → PR → STT → STJ

Florida ~1,100 Miles

Puerto Rico ~40 Miles

~3 Miles
Territory Characteristics

FL → PR → STT ↔ STJ ↔ STX

Puerto Rico ~40 Miles
Florida ~1,100 Miles

~40 Miles
~3 Miles

St. Thomas
St. John
St. Croix
Territory Characteristics

FL → PR → STT ↔ STJ
STJ ↔ STX → DI

Florida ~1,100 Miles
Puerto Rico ~40 Miles
“Down Island” ~3 Miles
~40 Miles
Storm Characteristics

FL → PR → STT ↔ STJ ↔ STX → DI
Storm Characteristics

FL → PR → STT ← STJ ← STX → DI
Storm Characteristics

FL → PR → STT
STJ
STX → DI

Irma
Sep 6-7
Storm Characteristics

FL → PR → STT → STJ → STX → DI

Irma, Sep 6-7

St. Thomas
St. John
St. Croix
Storm Characteristics

- FL → PR → STT
- STJ
- STX → DI

Irma

St. Thomas
St. John
St. Croix
Storm Characteristics

Flǔ → Pr → StT → STJ → STX → Di

Florida PR STT STJ DI

Irma Sep 6-7

St. Thomas St. John St. Croix
Storm Characteristics

Map showing the path of Hurricane Irma from Sep 6-7, 2017, affecting St. Thomas, St. John, St. Croix, and other islands in the Caribbean.
Storm Characteristics

STT → PR → STJ → STX → DI

- Irma: Sep 6-7
- Maria: Sep 20

Locations: St. Thomas, St. John, St. Croix
Storm Characteristics

St. Thomas
St. John
St. Croix

FL PR STT STJ DI

Maria
Irma
St. Thomas
St. John
St. Croix

Sep 6-7
Sep 20
September, 2017

Hurricanes Irma and Maria cause:

- Massive devastation to homes, businesses, and infrastructure
- Major loss of roadways, traffic lights, bridges, ports, and other transportation infrastructure
How Bad Was It?

- Estimated $10B in damages
  - $6.9B to infrastructure
- Roads
  - Curfew restrictions
  - Traffic lights out
  - Sevenfold increase in crashes
- Electricity
  - 90% of above ground lines damaged
  - Over 50% of poles knocked down
- Water
  - Reserves dropped to 3-day volume
  - Service restored after a month
- Telecommunications
  - 80% of towers down
  - Public radio/tv out for months
How we are taught Network Modeling...
How we are taught Network Modeling...

1. Download the data
How we are taught Network Modeling...

1. Download the data

2. Build model

```python
def build_master(nodes, arcs, attack_limit):
    model = pyo.ConcreteModel()
    model.Z = pyo.Var()
    model.n nodes = pyo.Set(initialize=nodes, ordered=True)
    model.arcs = pyo.Set(within=model.nodes, initialize=arcs)
    model.attack_limit = pyo.Param(initialize=attack_limit)
    model.Y = pyo.Var(model.arcs, within=pyo.Binary)

    def master_attack_limit(model):
        return sum(model.Y[i,j] for (i,j) in arcs) <= model.attack_limit
    model.master_attack_limit = pyo.Constraint(rule=master_attack_limit)

    model.cuts = pyo.ConstraintList()
    def master_objective_rule(model):
        return model.Z
    model.master_objective = pyo.Objective(rule=master_objective_rule,
                                           sense=pyo.maximize)
    return model
```
How we are taught Network Modeling...

1. Download the data

2. Build model

3. Conduct analysis
How we are taught Network Modeling...

1. Download the data

2. Build model

3. Conduct analysis
How we are taught Network Modeling...

My Naïve Understanding...

1. Download the data

2. Build model

3. Conduct analysis
How we are taught Network Modeling...

My Naïve Understanding...

1. Download the data

2. Build model

3. Conduct analysis
How we are taught Network Modeling...

1. Download the data

2. Build model

3. Conduct analysis??
Understand transportation infrastructure to support:

- Movement of goods into ports and onto stores via surface roads
- Movement of people from their homes to stores via surface roads
Understand transportation infrastructure to support:

- Movement of goods into ports and onto stores via surface roads
- Movement of people from their homes to stores via surface roads

Quantify impacts of:

- Imposed curfews
- Surface road restrictions or blockages
- Alternative relief locations
Understand transportation infrastructure to support:
• Movement of goods into ports and onto stores via surface roads
• Movement of people from their homes to stores via surface roads

Quantify impacts of:
• Imposed curfews
• Surface road restrictions or blockages
• Alternative relief locations

Goals:
• Maximize supply chain throughput
• Minimize household travel time
• Facilitate faster recovery
Model Overview

Based on an operational view of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

• Road and bridge inventory by type
Model Overview

Based on an *operational view* of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

• Road and bridge inventory by type

Does Not Exist
Model Overview

Based on an operational view of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

• Road and bridge inventory by type

• Population centers and their characteristics

Does Not Exist
Model Overview

Based on an operational view of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

• Road and bridge inventory by type

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Does Not Exist

Estates (2010 Census)
Model Overview

Based on an operational view of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes.

Data Requirements

- Road and bridge inventory by type
- Population centers and their characteristics
- Port schedules for containerized cargo
- Delivery schedules for major grocery stores, gas stations, or hardware stores
- Known shelter in place locations, both designated and non-designated

Does Not Exist

Estates (2010 Census)
Based on an *operational view* of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

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Does Not Exist

Estates (2010 Census)
Building the Data

USVI Site Visit: 24-29 March
- US Coast Guard
- Crowley Shipping
- Dept. of Public Works
- VI Port Authority
- FEMA Joint Field Office
Building the Data

USVI Site Visit: 24-29 March
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Road Survey
- Tourist Map
- Noted speeds
- Road conditions
- Potential relief points
- Stores
Building the Data
Building the Data
Building the Data

\[ y_{it} = \beta' x_{it} + \mu_i + \epsilon_{it} \]
Building the Data
Building the Data

[Diagram showing the process from .kml to .gpkg to pd.DataFrame]

- .kml
- .gpkg
- .gpkg
- pd.DataFrame
Building the Data

- .kml
- .gpkg
- .gpkg
- pandas
- .csv
- pd.DataFrame
- .csv
- Shiny
- R
- Python
- PYOMO
Building the Data

- .kml
- .gpkg
- pd.DataFrame
- .csv

Python

pandas

\[ y_{it} = \beta' x_{it} + \mu_i + \epsilon_{it} \]
Analysis: Estates
Analysis: Population “Centroids”
Actual location based on verification of homes and neighborhoods on Google Satellite view.
Analysis: Population Density by Estate
Analysis: Road Network
Analysis: Shortest Path Validation

Running program: ShortestPath.py
AllPoints file: ../../../Data/Working/STX/ModelPostTrip/AllPointsSTX.json
AdjList file: ../../../Data/Working/STX/ModelPostTrip/AdjDict.json
Origin Node: 0001
Destination Node: G025

The distance from 0001 to G025 is 31.164 km.
Analysis: Demand for Service by Estate (Shortest Path)

Radius of POINT OF INTEREST nodes indicates number of ORIGIN nodes serviced based on nearest neighbor.
Analysis: Demand for Service by Population (Shortest Path)

Radius of POINT OF INTEREST nodes indicates population of ORIGIN nodes serviced based on nearest neighbor.
Understanding Traffic Demand (Congestion): Delivery Model

Objective: \textbf{Maximize} supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW RT TIME (RTT)
Understanding Traffic Demand (Congestion): Delivery Model

Objective: **Maximize** supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW
RT TIME (RTT) = Load

 Stores

 Port

 Load
Objective: **Maximize** supply chain access

Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT) = **Load** + **Outbound**
Objective: *Maximize* supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW
RT TIME (RTT) = Load + **Outbound** + Unload
Understanding Traffic Demand (Congestion): Delivery Model

Objective: **Maximize** supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT) = Load + Outbound + Unload + Return
Objective: **Minimize** household travel time

Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW

RTT
Objective: Minimize household travel time
Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW
RTT = Outbound

Understanding Traffic Demand (Congestion): Customer Model
Understanding Traffic Demand (Congestion): Customer Model

Objective: **Minimize** household travel time

Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW

$RTT = \text{Outbound} + \text{Service Time}$
Objective: **Minimize** household travel time

Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW

RTT = Outbound + Service Time + Return
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

Port

Stores

Homes
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What is the port’s THROUGHPUT?
Understanding Traffic Demand (Congestion): Combined Model

**Shared**: Roads and Stores

What is the port’s THROUGHPUT?
What are the RTTs for the homes?
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What is the port’s THROUGHPUT?
What are the RTTs for the homes?
Where are the areas of CONGESTION?
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?

Port

Stores

Homes
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What if's?
Roads are blocked by electric poles?
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?
- Roads are blocked by electric poles?
- Port inaccessible?

Port

Stores

Homes
Understanding Traffic Demand (Congestion): Combined Model

**Shared:** Roads and Stores

**What ifs?**
Roads are blocked by electric poles?
Port inaccessible?
New Relief Point?

Port
Stores
Homes
Phases of Work

Phase 1 – Data Collection and Demand Modeling

- Curate and Validate Data
- Build network
- Validate traffic flow via shortest path
Phases of Work

Phase 1 – Data Collection and Demand Modeling
- Curate and Validate Data
- Build network
- Validate traffic flow via shortest path

Phase 2 – Congestion Modeling and Relief Point Analysis
- Equilibrium model of congestion based on road conditions and O-D pairs
- Calculate estate round trip times and analyze curfew impacts
- Estimate supply round trip times and calculate delivery volume per point of interest
Phases of Work

Phase 1 – Data Collection and Demand Modeling
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Phase 3 – Sponsor Outbriefs
- 2\textsuperscript{nd} Week of September - Next trip to USVI
  - Brief FEMA, Governor’s Office, UVI
- 27 September – Graduation (Expected)