Infrastructure Vulnerability & Resilience Inside & Outside the Fence Line

Daniel Eisenberg
Naval Postgraduate School

SERDP NICE Workshop
03 November 2022

SERDP
DOD ▪ EPA ▪ DOE

Center for Infrastructure Defense

www.nps.edu/cid

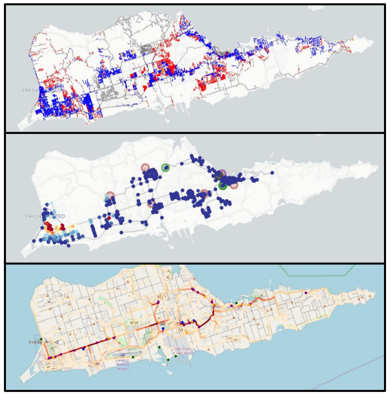
Director
Dr. David Alderson
Professor, Operations Research

Ph.D., Stanford University, 2003

Deputy Director
Dr. Daniel Eisenberg
Assistant Professor, Operations Research

Ph.D., Arizona State University, 2018

US Virgin Islands



NAVSTA Newport

Office of Naval Research Science & Technology ONR USN

DTRA DEFENSE THREAT REDUCTION AGENCY Detect. Deter. Defeat.

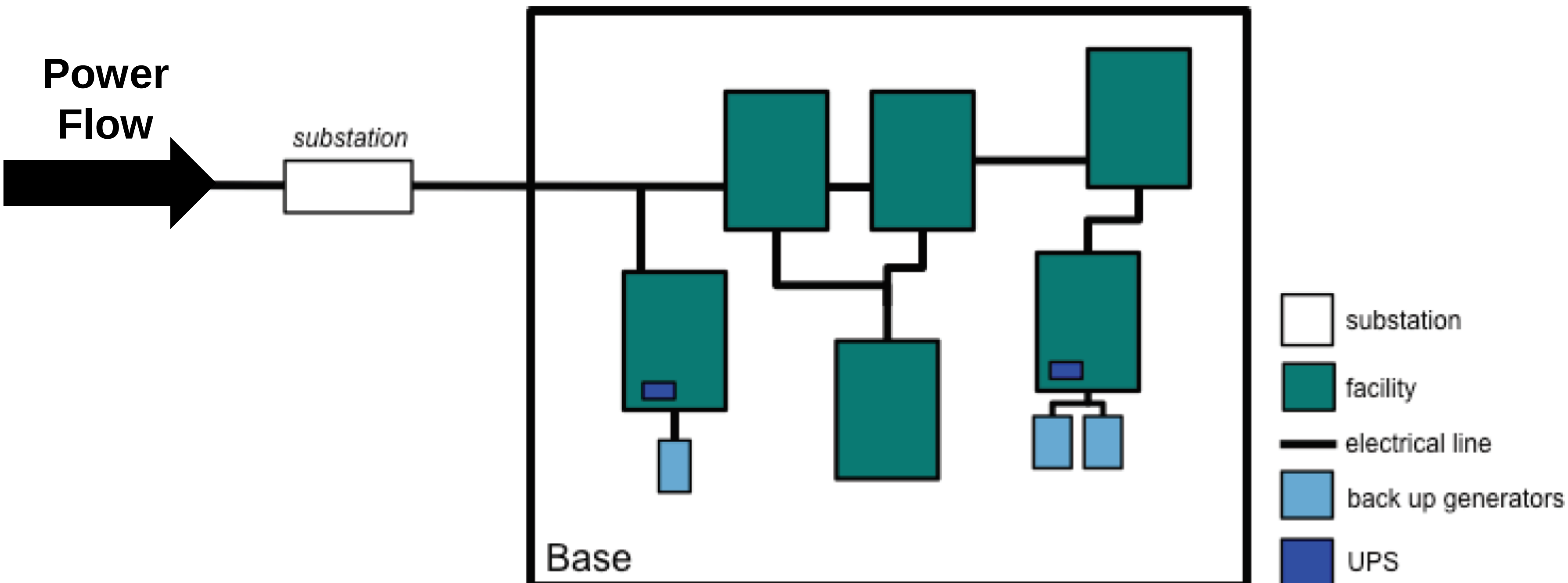
U.S. DEPARTMENT OF HOMELAND SECURITY FEMA

SERDP DOD • EPA • DOE

The Center for Infrastructure Defense (CID) focuses on the continued operation of critical military and civilian infrastructure in the presence of failure, natural disaster, attack, and surprise.

Motivation: Interdependent Infrastructure

Figure 3.1. Conceptual Diagram of CONUS Base Electric Power Physical Infrastructure



Narayanan et al. *Air Force Installation Energy Assurance*. RAND Corporation, 2017.

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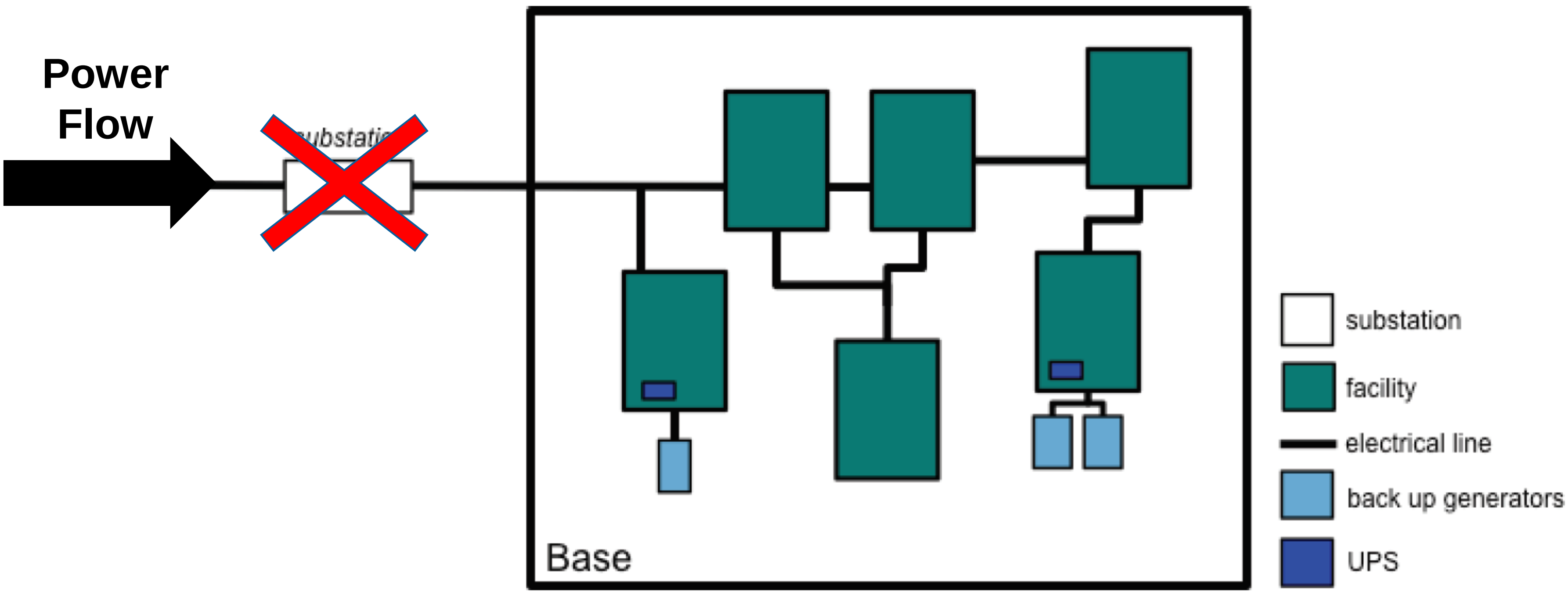
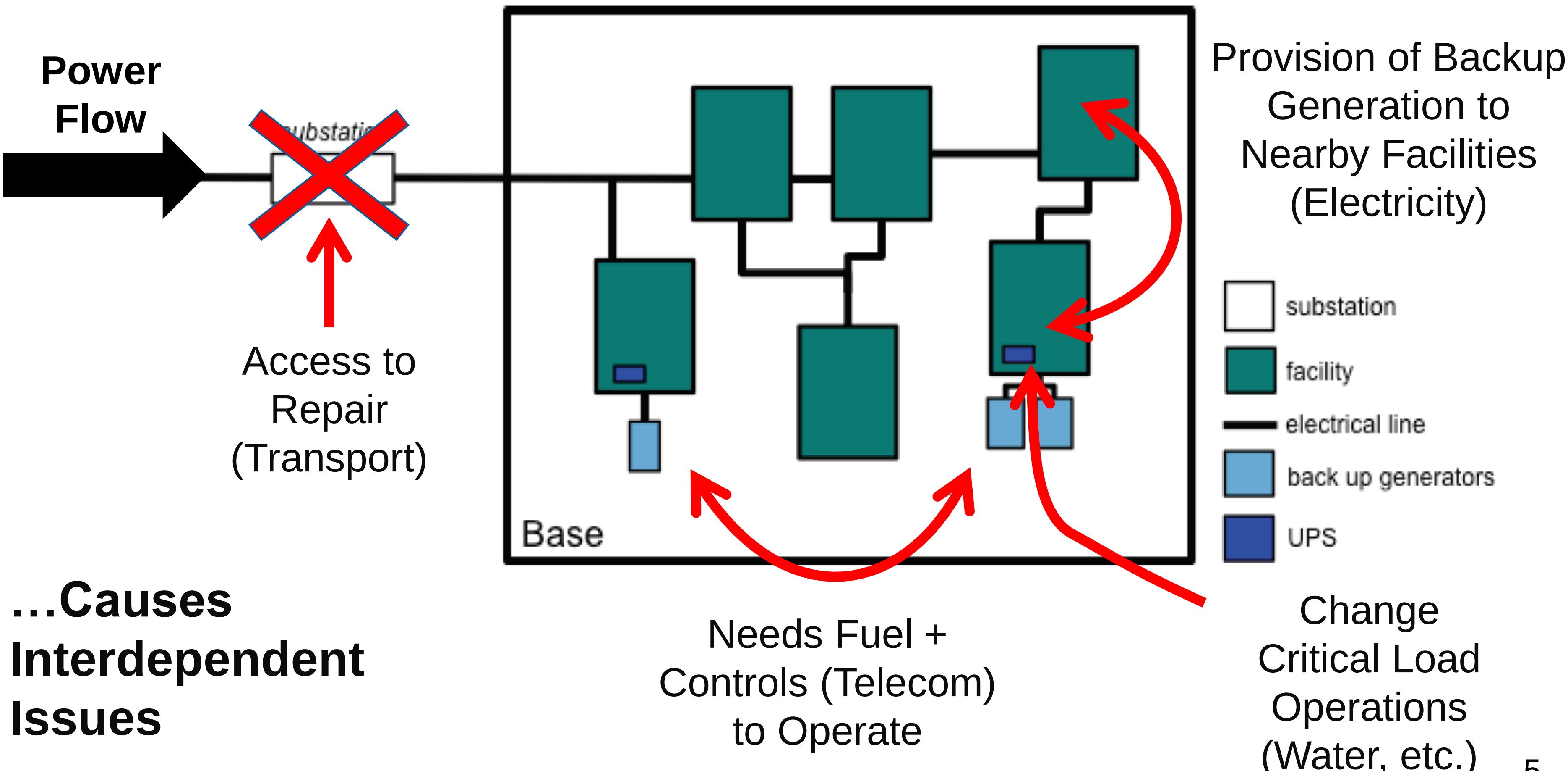


Substation Failure due to Compound Threat…

Motivation: Interdependent Infrastructure

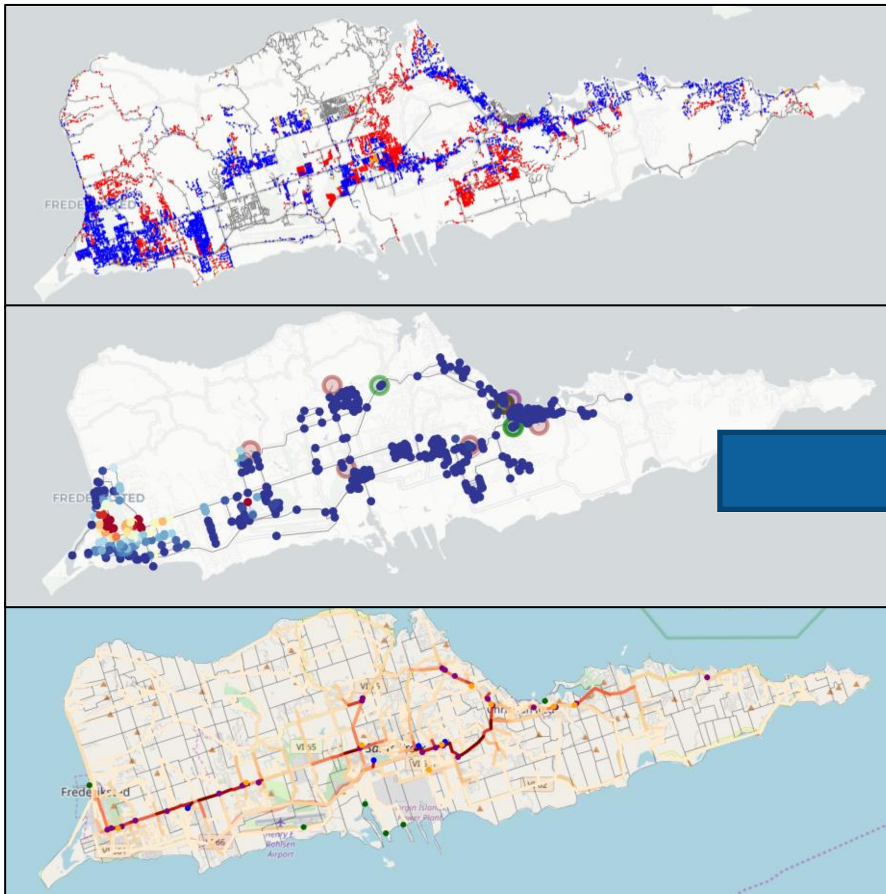
Figure 3.1. Conceptual Diagram of CONUS Base Electric Power Physical Infrastructure



…Causes Interdependent Issues

Goal: Apply Methods to DoD Problems

Civilian



Military

Identify Interdependent "Worst-Case" Compound Threats

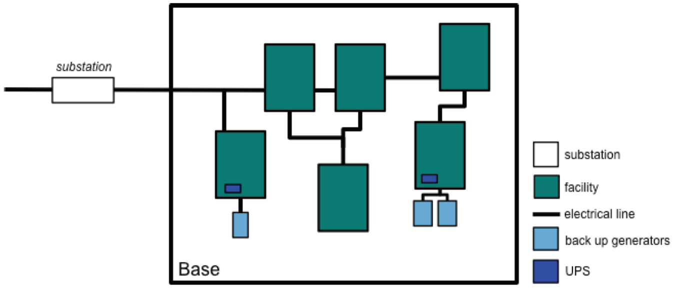
Energy, Water, Transportation, Telecom

MCB Hawaii

Research Inside & Outside the Fence Line

Inside the Fence Line

- Is there a framework for interdependent infrastructure modeling & analysis useful for installation vulnerability?
- How does the DoD relate infrastructure to mission?
- How is the DoD currently prioritizing their own infrastructure? Is it sufficient?



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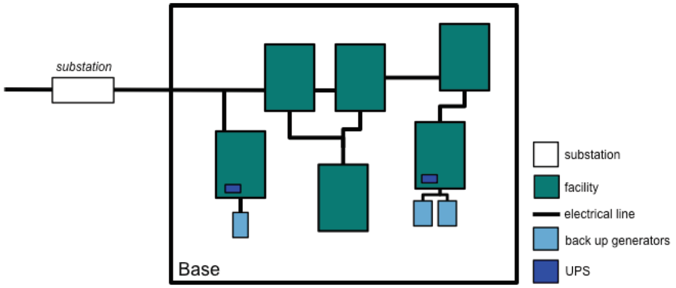
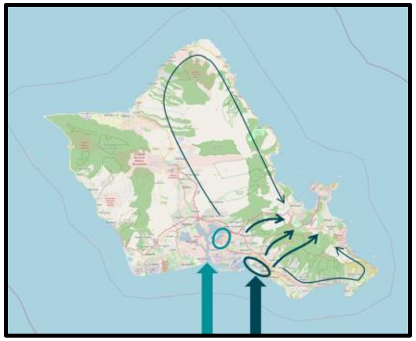


Outside the Fence Line

- How do community needs and infrastructure systems impact mission?
- How to better coordinate military installations and local communities during disasters?
- What investments outside the fence line support resilience?



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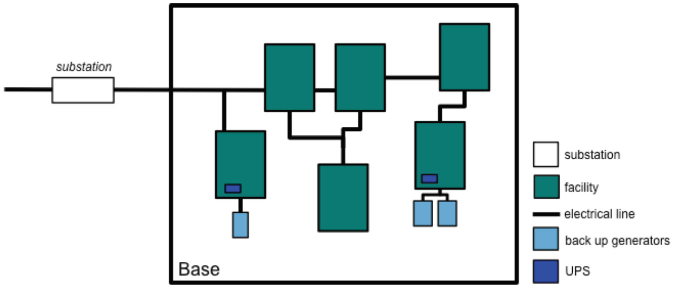

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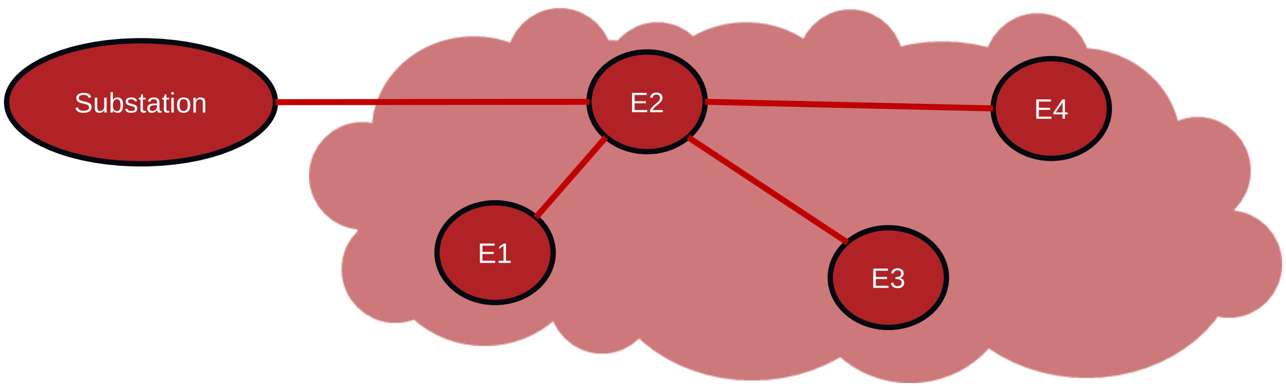
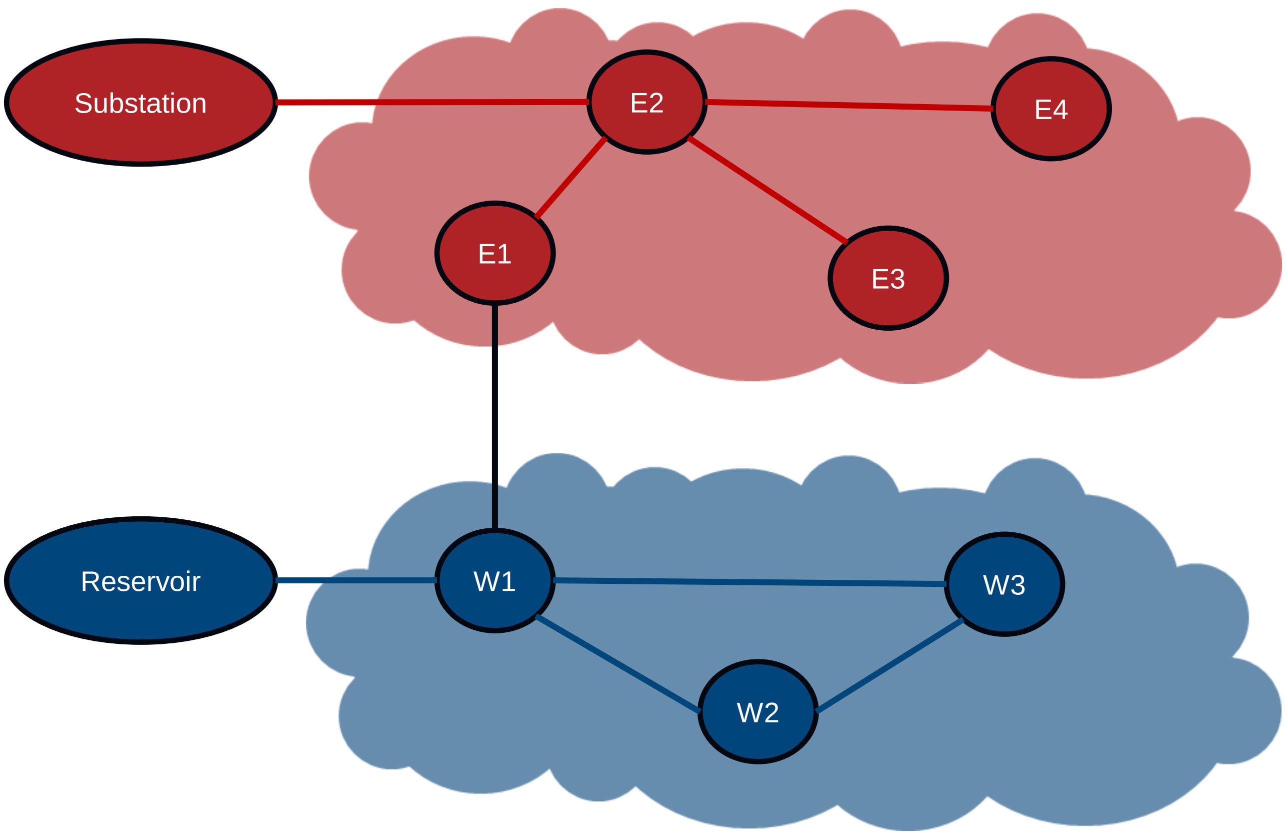
Multilayer Installation Networks



Electric Power Network

Multilayer Installation Networks

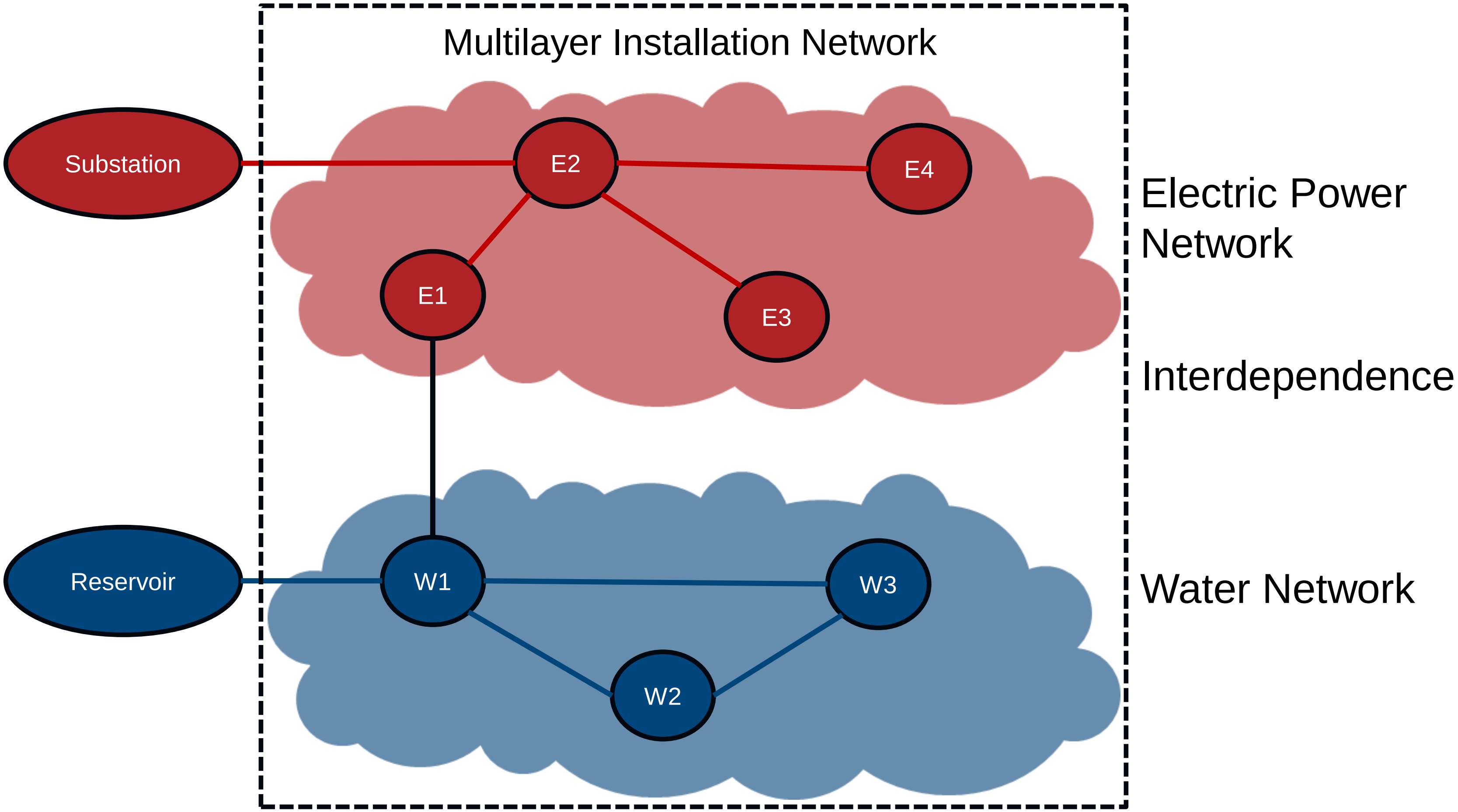


Electric Power Network

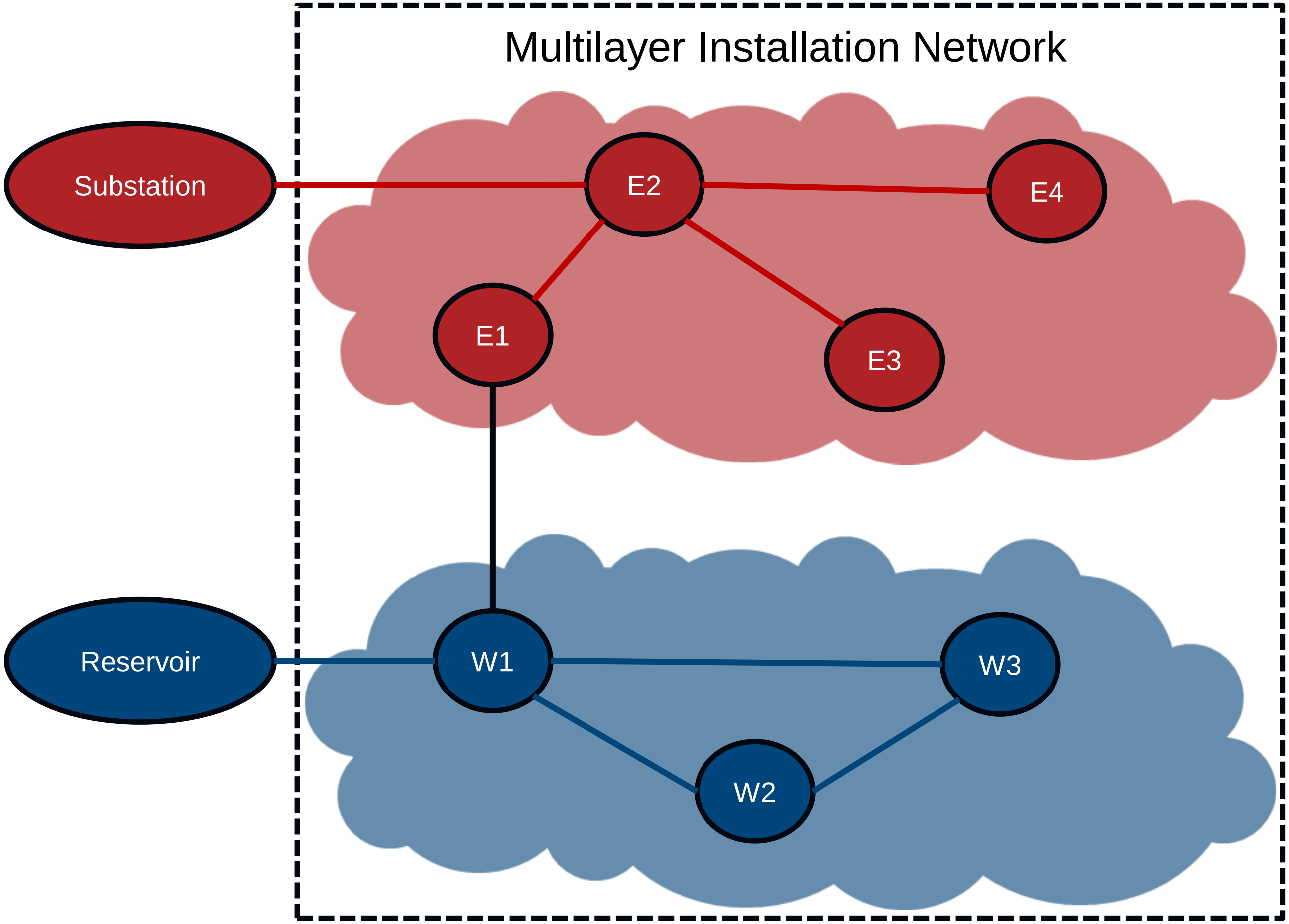
Interdependence

Water Network

Multilayer Installation Networks



Multilayer Installation Networks



Node-Colored Multilayer Network

$M = (V_c, E, C, \chi)$

$(E, W, \ldots) \in C$

$\chi: N_C \rightarrow C$

Electric Power Network

$G_E(V_E, E_E)$

Interdependence

$E_{EW} \subseteq E$

$E_{WE} \subseteq E$

Water Network

$G_W(V_W, E_W)$

Notation based on: Kivelä et al. (2014)

Multilayer Installation Networks

Interdependent Operator Models

Substation

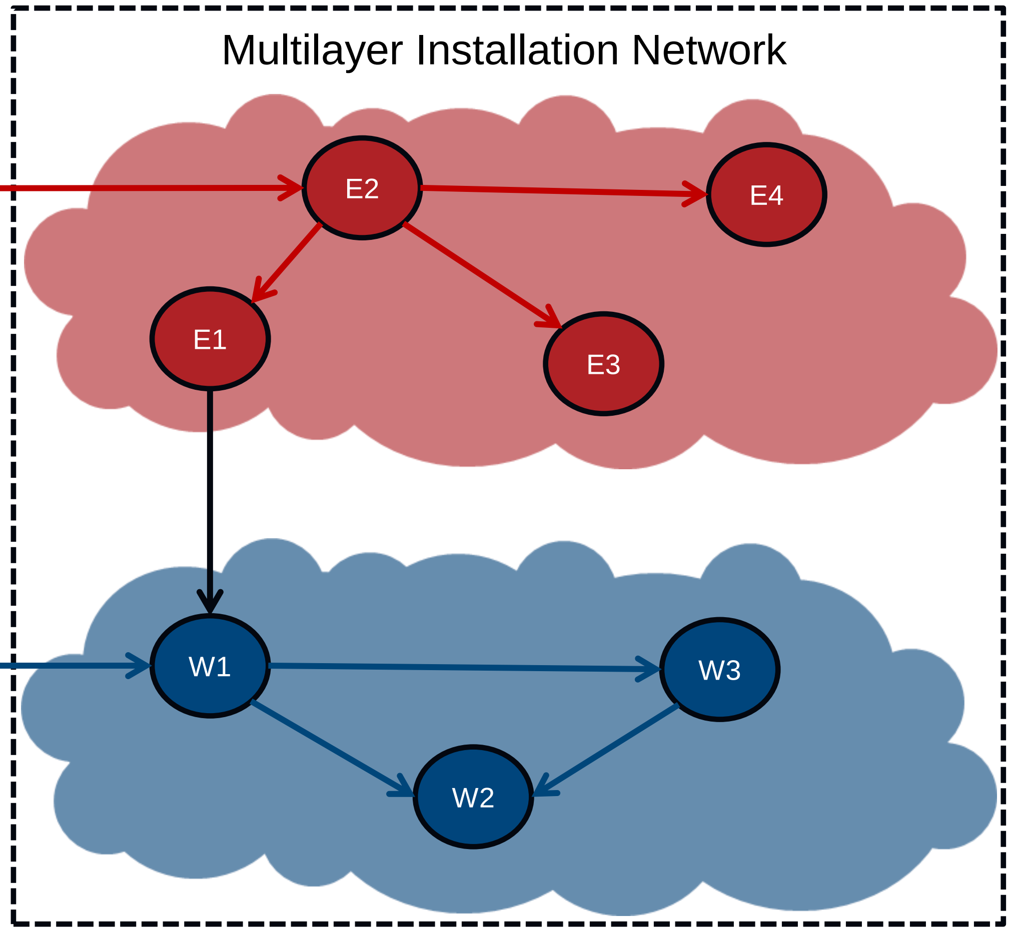
3 Phase AC Optimal Power Flow

$$\min \sum_{i \in N, k \in P} lp_{i,k} + lq_{i,k}$$

Reservoir

Hydraulic Balancing

$$\sum_{p \in P_n} q_{p,n} - D_n^{act} = 0$$



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Water Network

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Notation based on: Kivelä et al. (2014)

PowerWaterModels.jl Documentation

Overview

PowerWaterModels.jl is a Julia/JuMP package for the joint optimization of steady-state power and water distribution networks. It is designed to enable the computational evaluation of historical and emerging power-water network optimization formulations and algorithms using a common platform. The code is engineered to decouple Problem Specifications (e.g., power-water flow, optimal power-water flow) from Network Formulations (e.g., mixed-integer linear, mixed-integer nonlinear). This decoupling enables the definition of a variety of optimization formulations and their comparison on common problem specifications.

Installation

The latest stable

```
] add PowerW
```

For the current c

```
] add PowerW
```

Finally, test that

Constraints

We define the following methods to provide a compositional approach toward defining linking constraints used in coupled power-water models. Such methods should always be defined over `AbstractPowerWaterModel`.

`PowerWaterModels.constraint_fixed_load` — Method

Constraint for modeling a fixed load (i.e., not connected to a pump). Since the base power formulation uses a variable, $0 \leq z_{it} \leq 1$, to model the proportion of maximum load served at load $i \in \mathcal{L}$, time index $t \in \mathcal{T}$, a value of one indicates the full load being served, as expected for non-pump loads. That is, these constraints are

$$z_{it} = 1, \forall i \in \mathcal{L}', \forall t \in \mathcal{T},$$

where $\mathcal{L}'$ is the set of loads not connected to a pump.

source

`PowerWaterModels.constraint_pump_load` — Method

Constraint for modeling a variable load (i.e., connected to a pump). Since the base power formulation uses a variable, $0 \leq z_{it} \leq 1$, to model the proportion of maximum load served at load $i \in \mathcal{L}$, time index $t \in \mathcal{T}$, a value of one indicates the maximum load is being served (denoted as pd). Any other value will represent some proportion of this maximum. Linking pump power to load is thus modeled via

$$P_{jt} = z_{it} \sum_{c \in \mathcal{C}} pd_{ict}, \forall (i, j) \in \mathcal{D}, \forall t \in \mathcal{T},$$

where $\mathcal{D}$ is the set of interdependencies, linking loads, $i \in \mathcal{L}$, to pumps, $j \in \mathcal{P}$. Here, P_j is a variable that represents pump power and $\mathcal{C}$ is the set of conductors, i.e., power is bounded by $\sum_{c \in \mathcal{C}} pd_{ict}$.

The PowerWaterModels.jl problem (Uber Model):

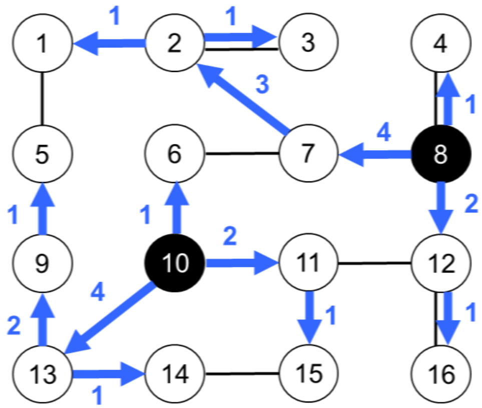
- Calls and installs external packages (PowerModels, WaterModels)
- Interdependencies handled using two constraints added as a separate file.
- Run as standalone package

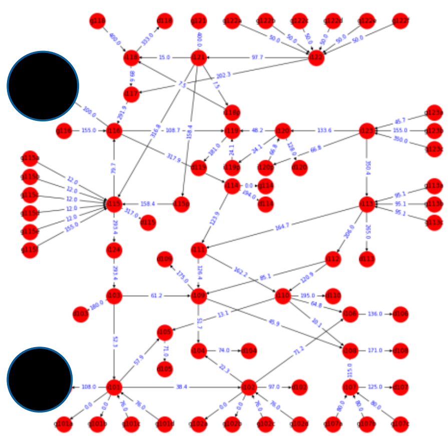
Makes it hard for non-experts to understand

Limits flexibility for other systems to be included

Interdependency Framework (Maj Kuc 2020)

Fuel Network





Power Network

Fuel Network Model

- Objective for Fuel Delivery
- Constraints for Fuel Delivery

Power Network Model

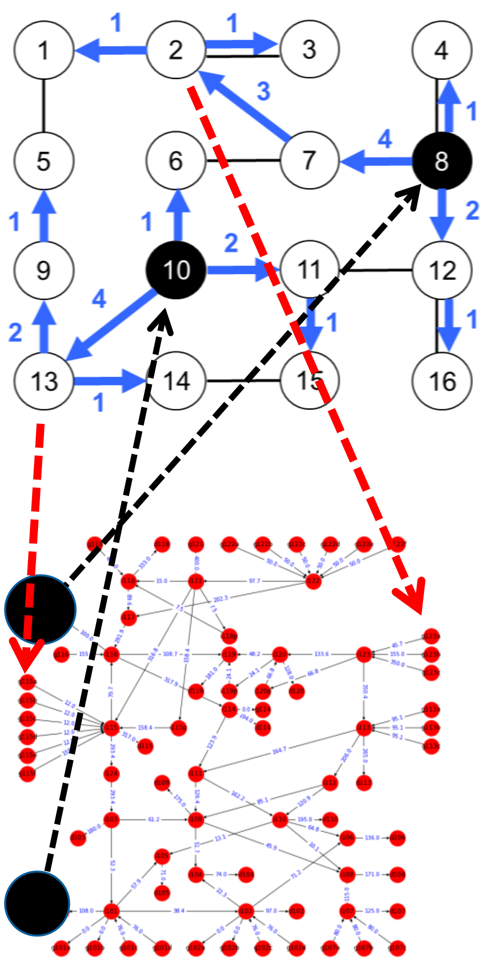
- Objective for Power Delivery
- Constraints for Power Delivery

Process for Interdependent Infrastructure Analysis:

1. Make Domain-specific Operational Models

Interdependency Framework (Maj Kuc 2020)

Fuel Network



Power Network

Fuel Network Model

Objective for Fuel Delivery

Constraints for Fuel Delivery

Constraints for Fuel on Power

Power Network Model

Objective for Power Delivery

Constraints for Power Delivery

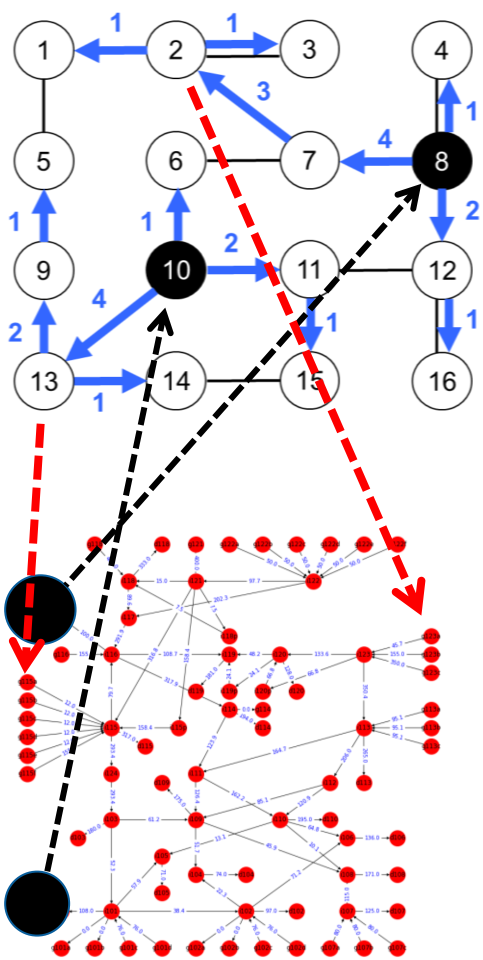
Constraints for Power on Fuel

Process for Interdependent Infrastructure Analysis:

2. Develop Interdependency Constraints and Data sets

Interdependency Framework (Maj Kuc 2020)

Fuel Network



Power Network

- Fuel Network Model
  - Objective for Fuel Delivery
  - Constraints for Fuel Delivery
  - Constraints for Fuel on Power
- Power Network Model
  - Objective for Power Delivery
  - Constraints for Power Delivery
  - Constraints for Power on Fuel

Process for Interdependent Infrastructure Analysis:

3. Combine into a Single “Uber” Model for Analysis

- Interdependent Network Model
  - Objective
  - Objective
  - Constraints for Fuel Delivery
  - Constraints for Power Delivery
  - Constraints for Fuel on Power
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Interdependency Framework (Maj Kuc 2020)

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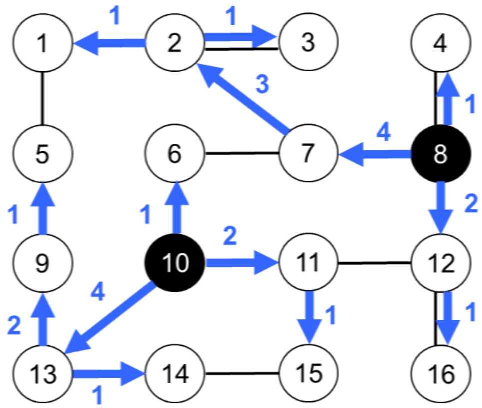


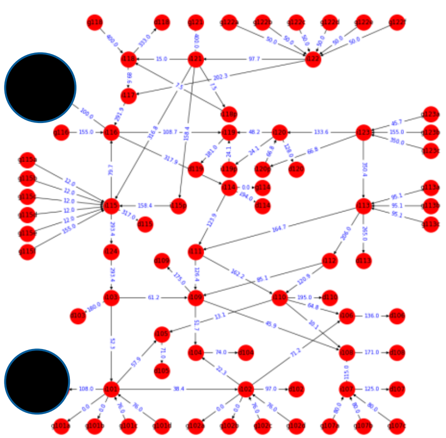
Fuel Network Model

Objective for Fuel Delivery

Constraints for Fuel Delivery

***New* Process for Interdependent Infrastructure Analysis:**

1. Make Domain-specific Operational Models



Power Network

Power Network Model

Objective for Power Delivery

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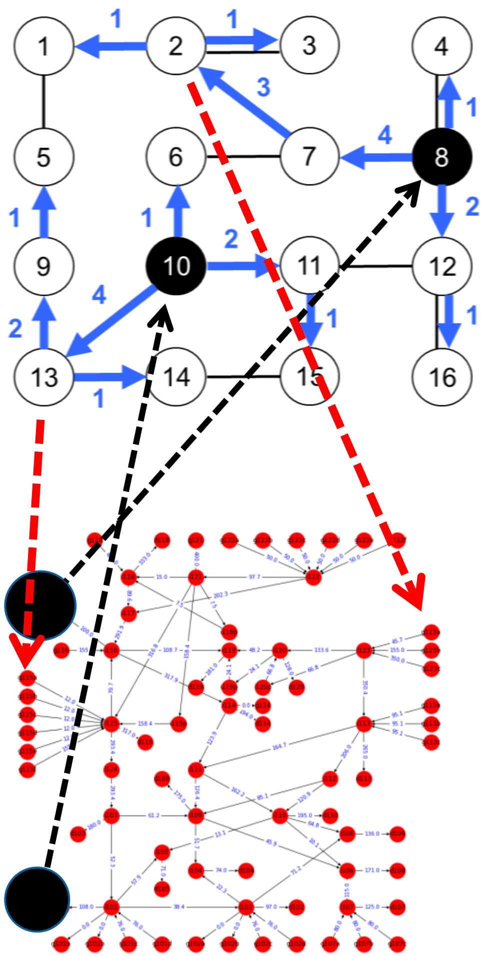
Interdependency Framework (Maj Kuc 2020)

Fuel Network



Power Network

Fuel Network Model

- Objective for Fuel Delivery
- Constraints for Fuel Delivery

+

Power Network Model

- Objective for Power Delivery
- Constraints for Power Delivery

***New* Process for Interdependent Infrastructure Analysis:**

2. Run Combo-Model Generator Function → Interdependent Model

Interdependent Network Model

- Objective
- Objective
- Constraints for Fuel Delivery
- Constraints for Power Delivery
- Constraints for Fuel on Power
- Constraints for Power on Fuel

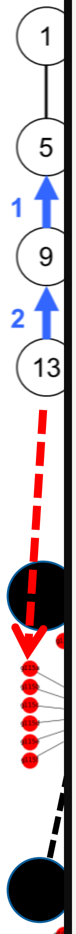
Based on work by: Ahangar et al. "Modeling interdependencies in infrastructure systems using multi-layered network flows." Computers & Operations Research 117 (2020): 104883.

Interdependency Framework (Maj Kuc 2020)

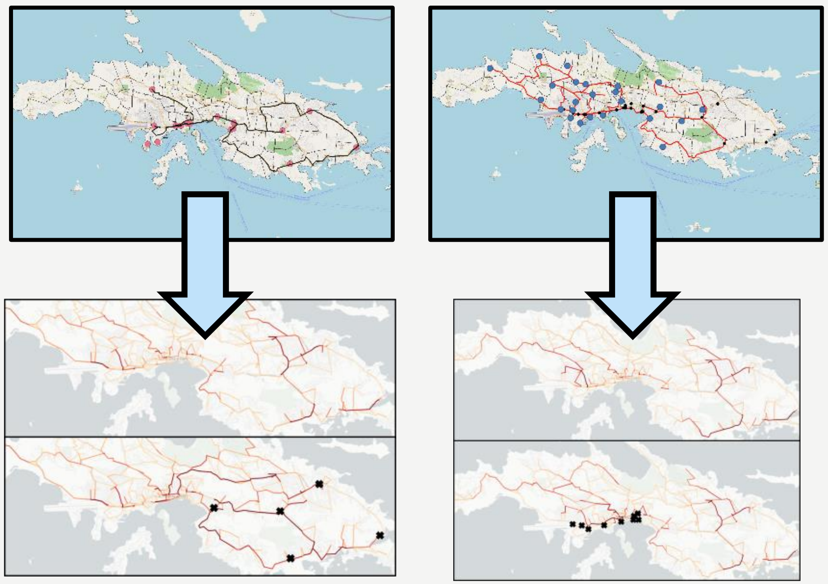
Fuel Network

Fuel Network

New **Process for Interdependent**



This Process Enables the Better Development of Interdependent Infrastructure Models



- More easily combine models developed in isolation by non-experts
- Supports more flexible interdependent infrastructure analysis

Enables more effective vulnerability analysis to compound threats

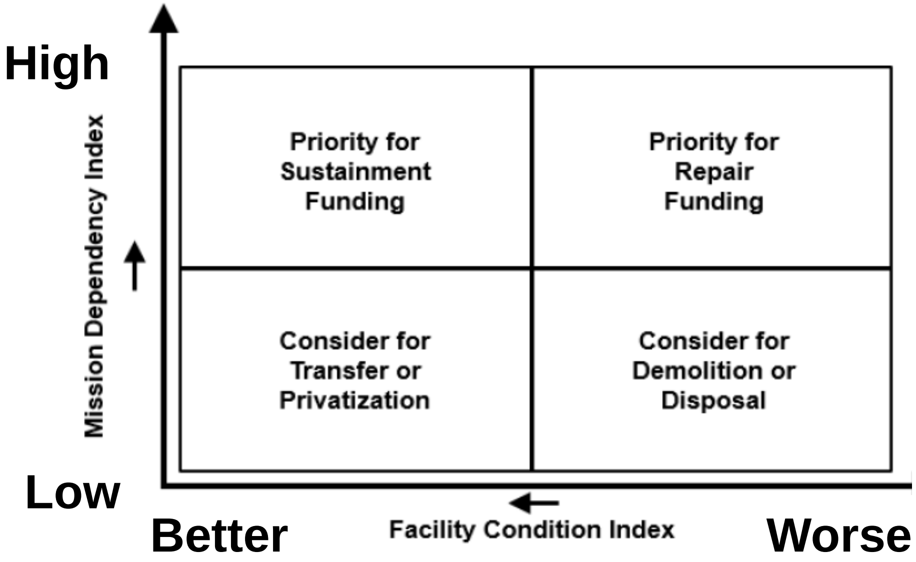
Power Network

Constraints for Power on Fuel

Mission Dependency Index

Funding Decisions are Made with the Mission Dependency Index (MDI)

- Facility Condition Index (FCI): Measure of quality
- Mission Dependency Index (MDI): Measure of capability



From: Nichols (2015)

FY21 Expenditures using MDI & FCI

Agency	$	Source
USN	3,523.1	Chief Financial Officer, Comptroller
USAF	3,388.5	Chief Financial Officer, Comptroller
USA	3,882.1	Chief Financial Officer, Comptroller
NASA	539.1	National Aeronautics and Space Administration
DOE	8,613.4	Office of Chief Financial Officer
Total	19,946.2	* Figures are based from FY21 projections

From: Eisenberg et al. (2022)

Mission Dependency Index

Mission Dependency Index: Two Key Steps

1. Expert elicitation to determine mission-essential assets and facilities. Produces measures of mission dependency ***within*** and ***between*** missions.

Interruptibility Score
None (N)
Brief (B)
Short (S)
Prolonged (P)

Relocatability / Replaceability Score
Impossible (I)
Extremely Difficult (X)
Difficult (D)
Possible (P)

MD_W		Q1: Interruptibility			
		None	Briefly	Short	Prolonged
		Available 24hrs/7 days	≤ 24 hrs	1 – 7 days	≤ 7 days
Q2: Relocatability	Impossible	6.00	5.50	4.67	3.67
	X_Difficult	5.10	4.43	3.43	2.60
	Difficult	4.90	4.23	3.23	2.40
	Possible	4.00	3.00	2.00	1.00

MD_B		Q3: Interruptibility			
		None	Briefly	Short	Prolonged
		Available 24hrs/7 days	≤ 24 hrs	1 – 7 days	≤ 7 days
Q4: Replaceability	Impossible	6.00	5.50	4.67	3.67
	X_Difficult	5.10	4.43	3.43	2.60
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2. Integration into normalized score that is sent up the decision chain within the DoD **to guide funding decisions.**

MDI Category	Score Range
CRITICAL	100-85
SIGNIFICANT	84-70
RELEVANT	69-55
MODERATE	54-40
LOW	39-1

Mission Dependency Index

Missio
Index:

1. Exp
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measu
depend
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2. Inte
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chain w
guide funding decisions.

LOW	39-1

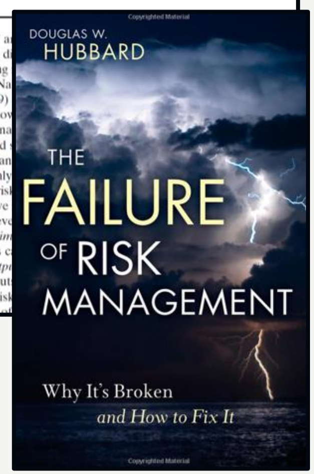
How Probabilistic Risk Assessment Can Mislead Terrorism Risk Analysts

Gerald G. Brown[1] and Louis Anthony (Tony) Cox, Jr.[2,*]

What's Wrong with Risk Matrices?

Louis Anthony (Tony) Cox, Jr.*

Risk matrices—tables mapping "frequency" a
ority levels—are popular in applications as d
struction project management, office building
and enterprise risk management (ERM). Na
tary Standard 882C and AS/NZS 4360:1999)
many organizations and risk consultants. How
performance in actually improving risk mana
mathematical properties of risk matrices and
(a) *Poor Resolution*. Typical risk matrices can
small fraction (e.g., less than 10%) of randomly
tical ratings to quantitatively very different risk
trices can mistakenly assign higher qualitative
with negatively correlated frequencies and seve
to worse-than-random decisions. (c) *Suboptim*
resources to risk-reducing countermeasures c
risk matrices. (d) *Ambiguous Inputs and Outp*
objectively for uncertain consequences. Input
categorizations) and resulting outputs (i.e., risk

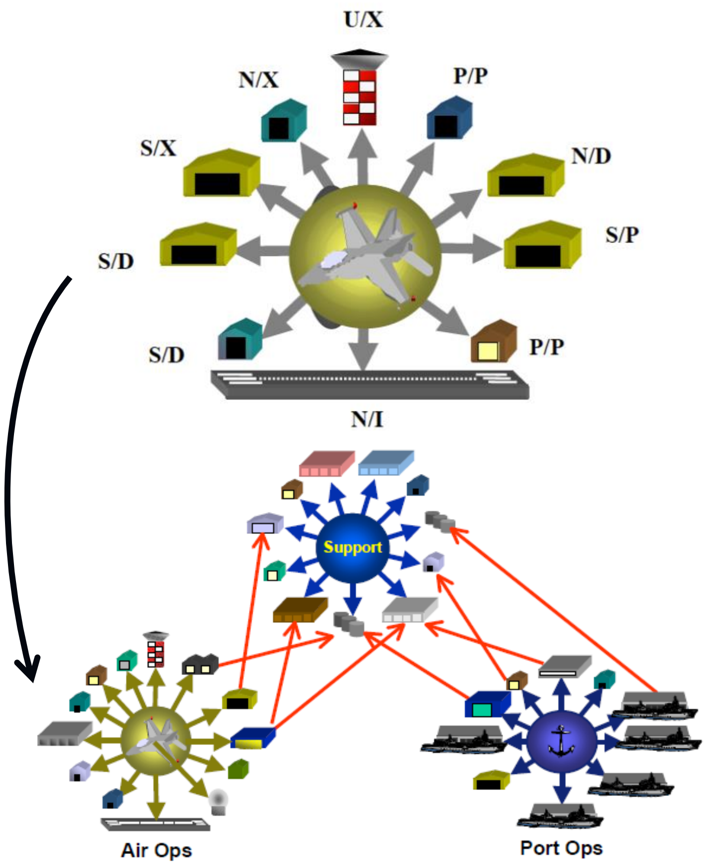


This has known issues...

- Risk matrices and ordinal scales can produce misleading prioritization.
- Expert elicitation can produce skewed and inappropriate scores

MDI & Interdependent Networks

MDI Analysis Intent



MDI & Interdependent Networks

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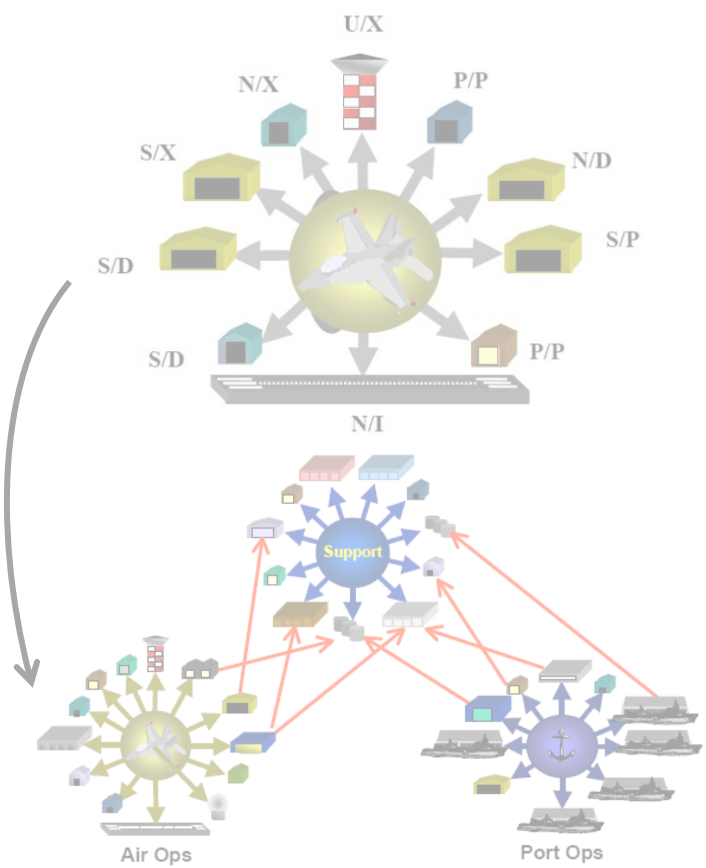
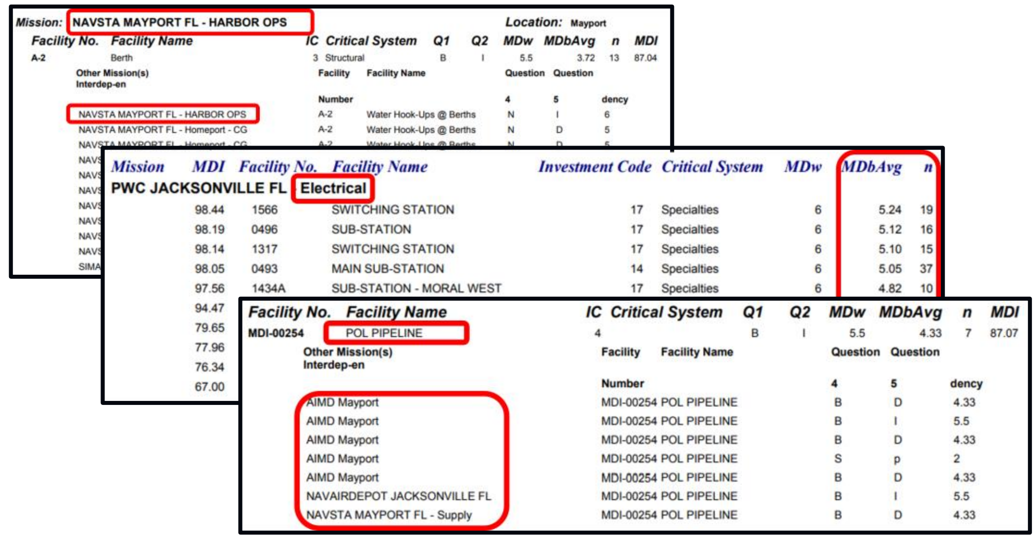


MDI Analysis Reality



Mission: NAVSTA MAYPORT FL - HARBOR OPS — Location: Mayport

Facility No.	Facility Name	IC	Critical System	Q1	Q2	MDw	MDbAvg	n	MDI
A-2	Berth	3	Structural	B	I	5.5	3.72	13	87.04

Other Mission(s) Interdep-en	Facility Number	Facility Name	Question 4	Question 5	dency
NAVSTA MAYPORT FL - HARBOR OPS	A-2	Water Hook-Ups @ Berths	N	I	6
NAVSTA MAYPORT FL - Homeport - CG	A-2	Water Hook-Ups @ Berths	N	D	5

Mission	MDI	Facility No.	Facility Name	Investment Code	Critical System	MDw	MDbAvg	n
PWC JACKSONVILLE FL	Electrical							
	98.44	1566	SWITCHING STATION	17	Specialties	6	5.24	19
	98.19	0496	SUB-STATION	17	Specialties	6	5.12	16
	98.14	1317	SWITCHING STATION	17	Specialties	6	5.10	15
	98.05	0493	MAIN SUB-STATION	14	Specialties	6	5.05	37
	97.56	1434A	SUB-STATION - MORAL WEST	17	Specialties	6	4.82	10
	94.47							
	79.65							
	77.96							
	76.34							
	67.00							

Facility No.	Facility Name	IC	Critical System	Q1	Q2	MDw	MDbAvg	n	MDI
MDI-00254	POL PIPELINE	4		B	I	5.5	4.33	7	87.07

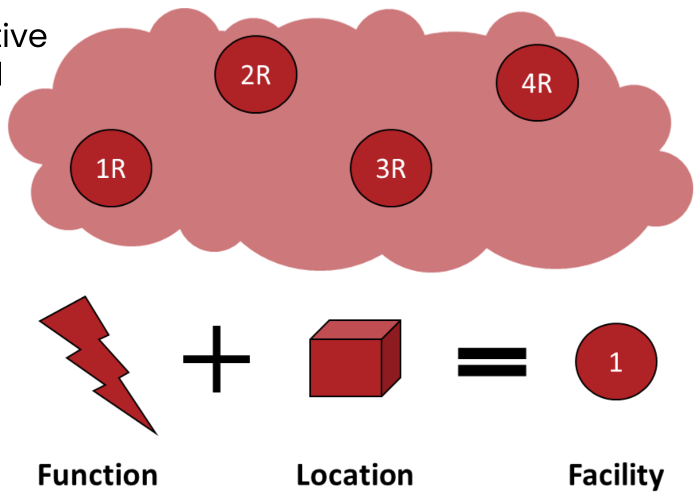
Other Mission(s) Interdep-en	Facility Number	Facility Name	Question 4	Question 5	dency
AIMD Mayport	MDI-00254	POL PIPELINE	B	D	4.33
AIMD Mayport	MDI-00254	POL PIPELINE	B	I	5.5
AIMD Mayport	MDI-00254	POL PIPELINE	B	D	4.33
AIMD Mayport	MDI-00254	POL PIPELINE	S	p	2
AIMD Mayport	MDI-00254	POL PIPELINE	B	D	4.33
NAVAIRDEPOT JACKSONVILLE FL	MDI-00254	POL PIPELINE	B	I	5.5
NAVSTA MAYPORT FL - Supply	MDI-00254	POL PIPELINE	B	D	4.33

No one has any idea about the networks and measures they produce.

- No way to compare analysis from one installation to another.
- No way to compare with networks literature to develop models, metrics, measures, etc.

MDI as a Multilayer Network (LCDR Fish 2021)

Administrative
Mission Red



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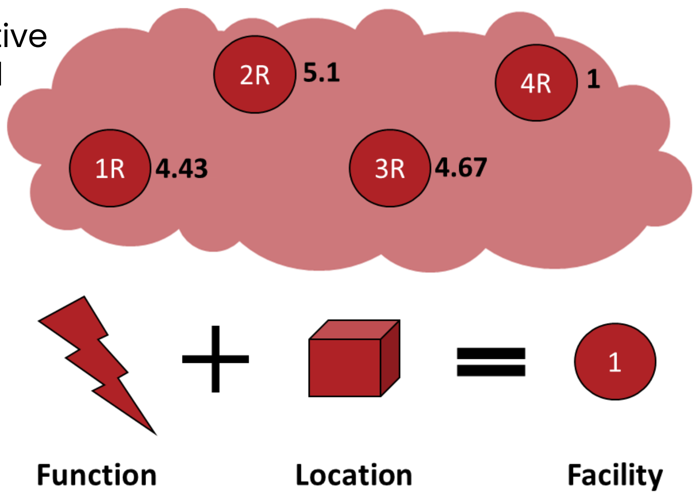

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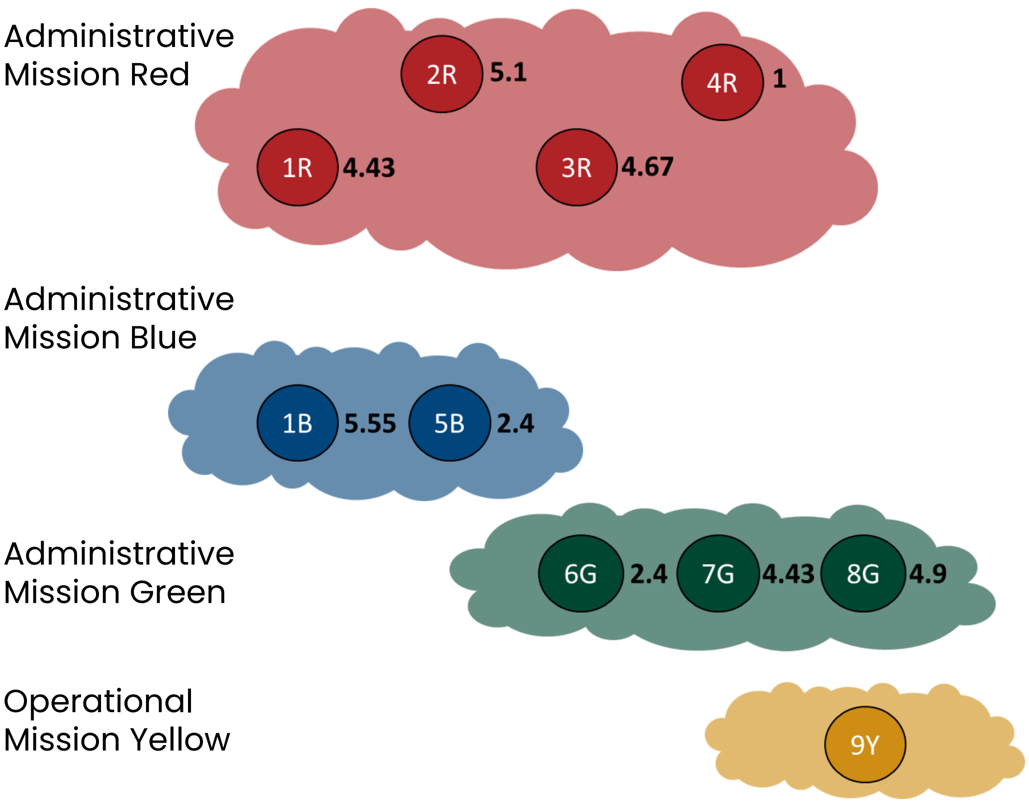
Importance of facilities within a single mission measured with MD_W

MDI as a Multilayer Network (LCDR Fish 2021)



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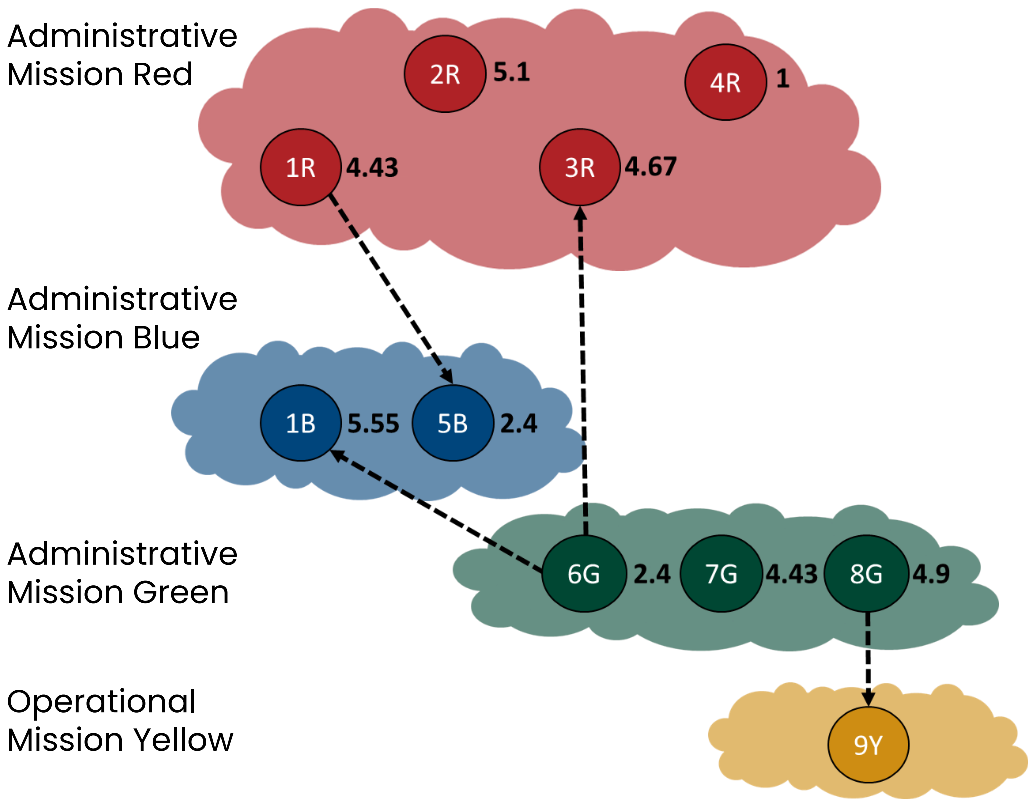

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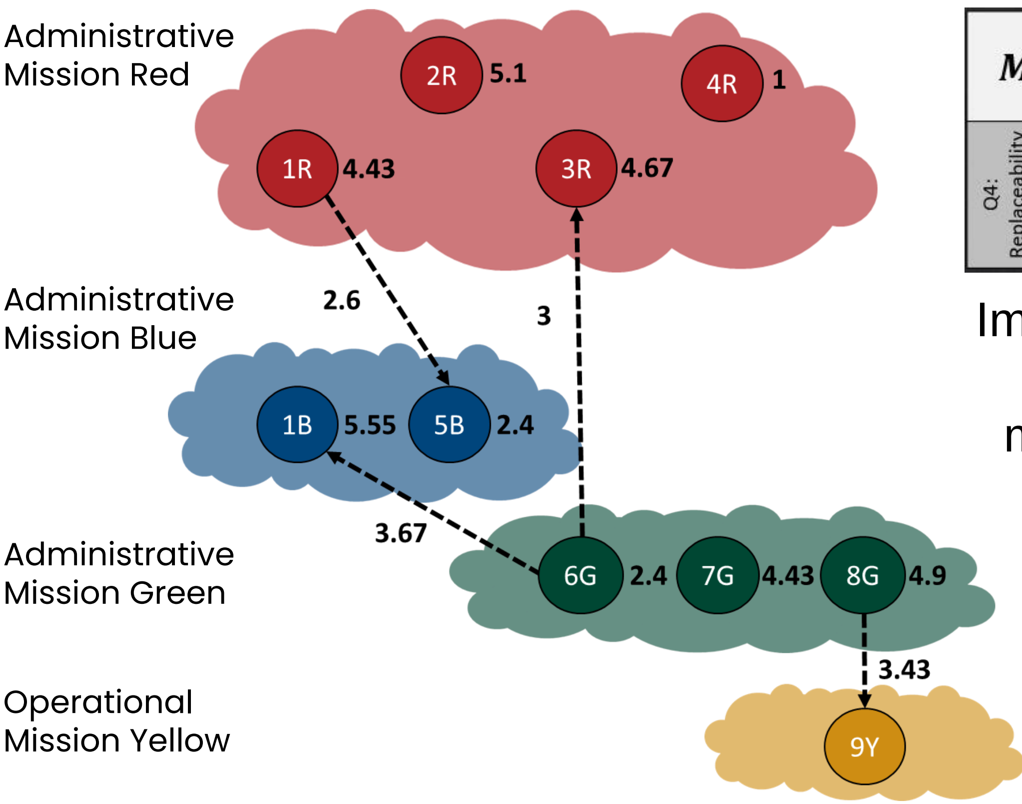
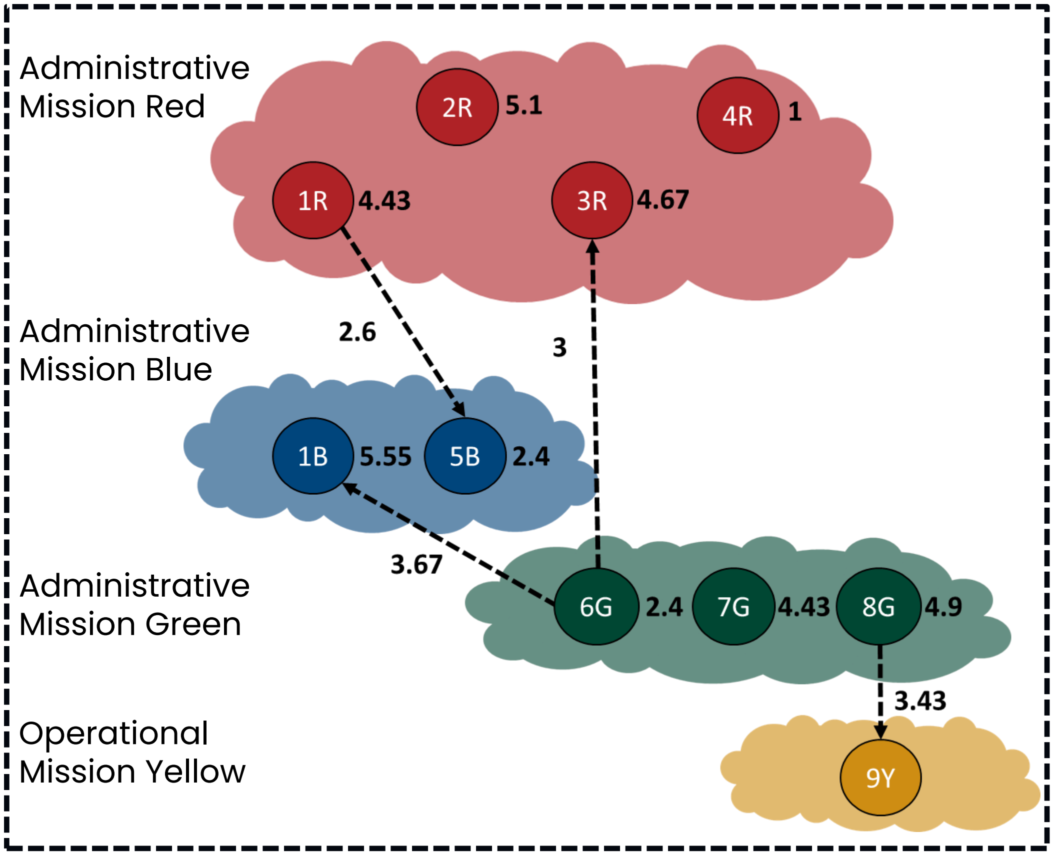


MD_B		Q3: Interruptability			
		None	Briefly	Short	Prolonged
		Available 24hrs/7 days	≤ 24 hrs	1 − 7 days	≤ 7 days
Q4: Replaceability	Impossible	6.00	5.50	4.67	3.67
	X_Difficult	5.10	4.43	3.43	2.60
	Difficult	4.90	4.23	3.23	2.40
	Possible	4.00	3.00	2.00	1.00

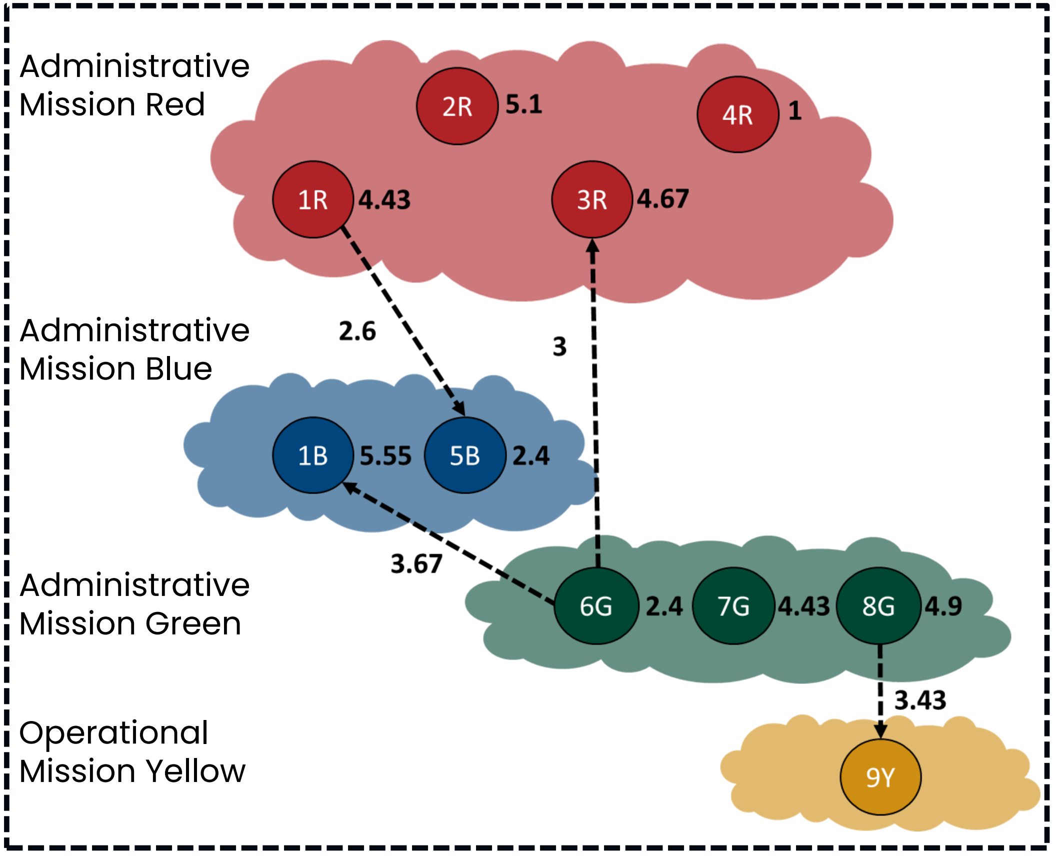
Importance of facilities between missions measured with MD_B

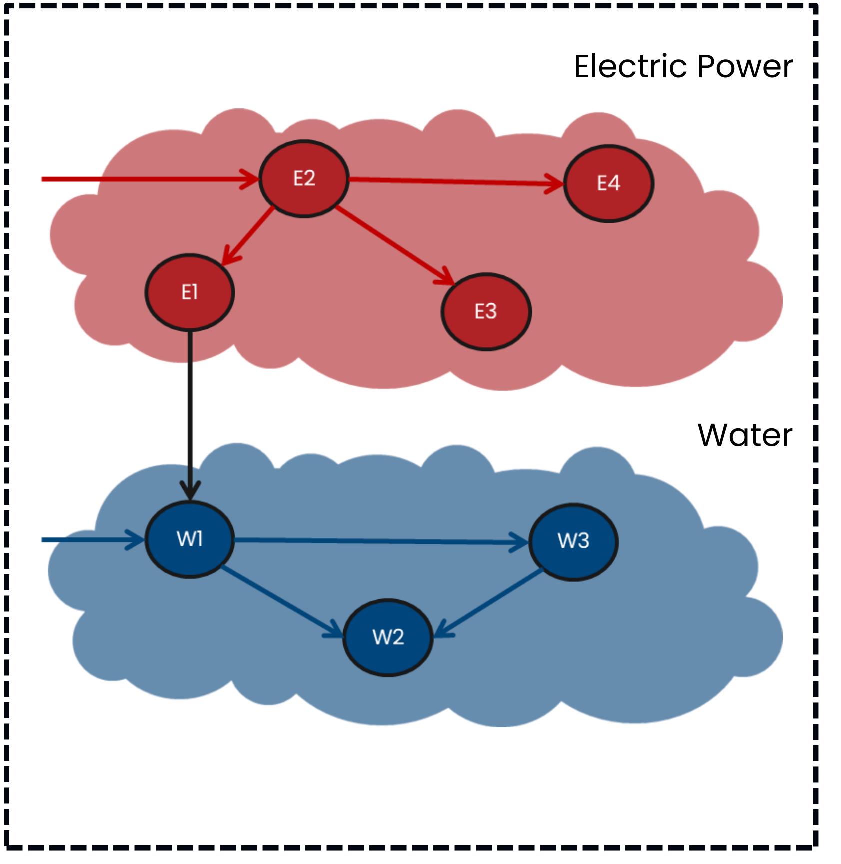
MDI as a Multilayer Network (LCDR Fish 2021)



MDI as a Multilayer Network (LCDR Fish 2021)

Comparing Systems... Lots of Problems!





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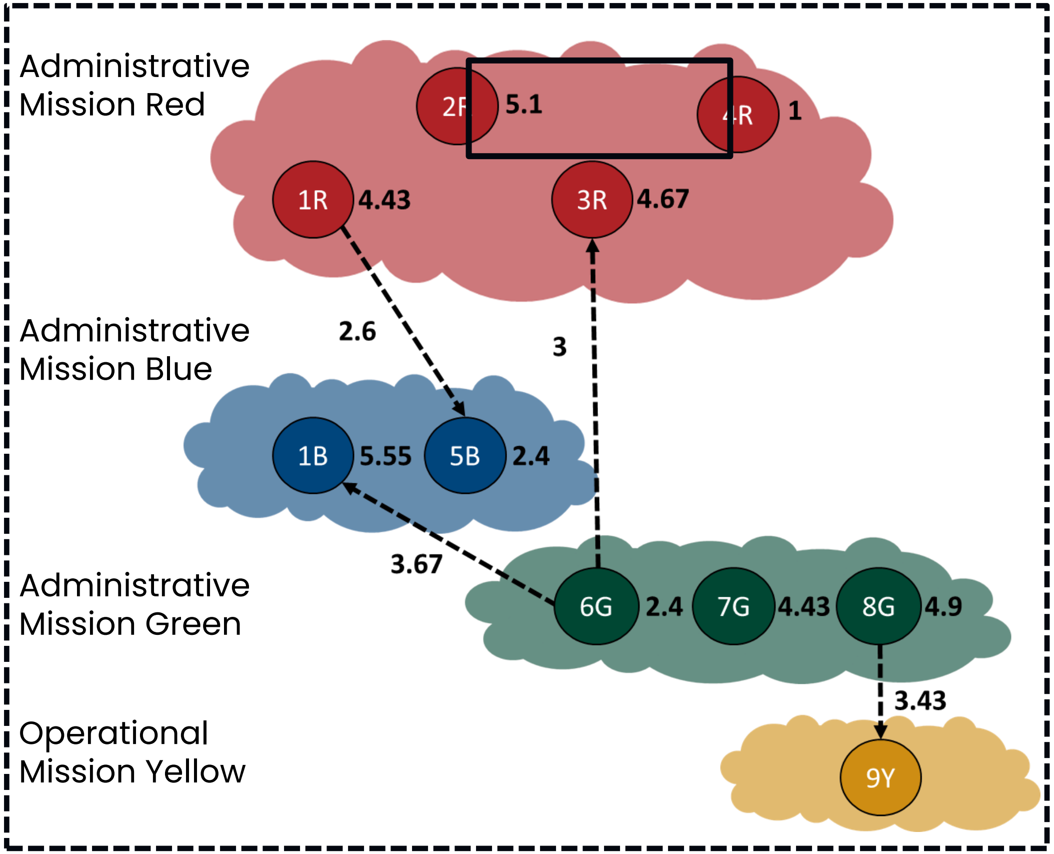

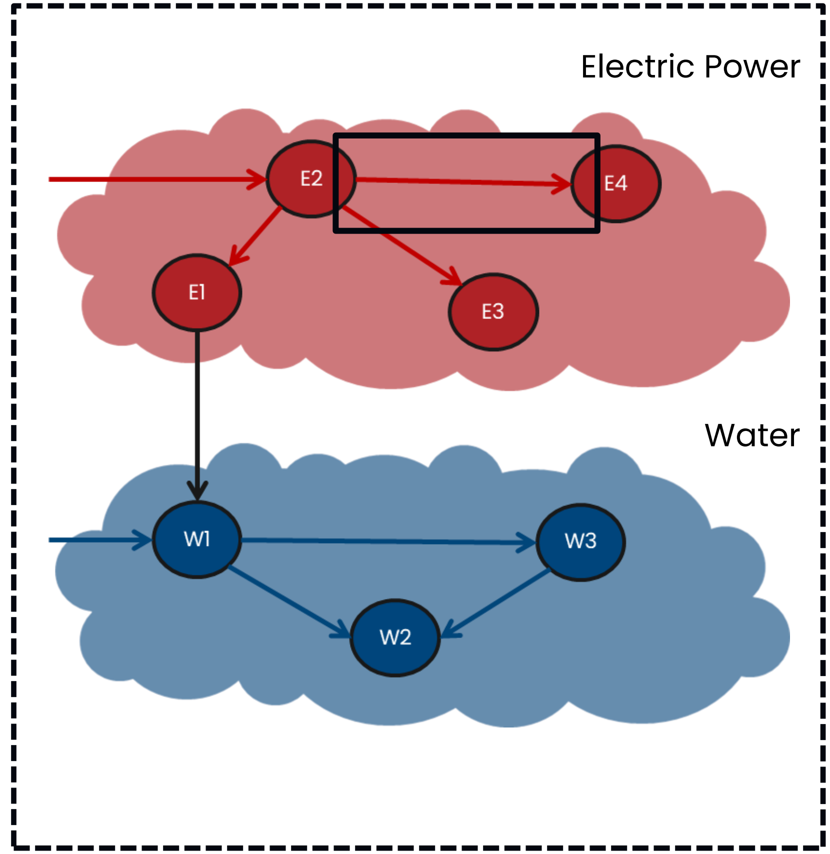

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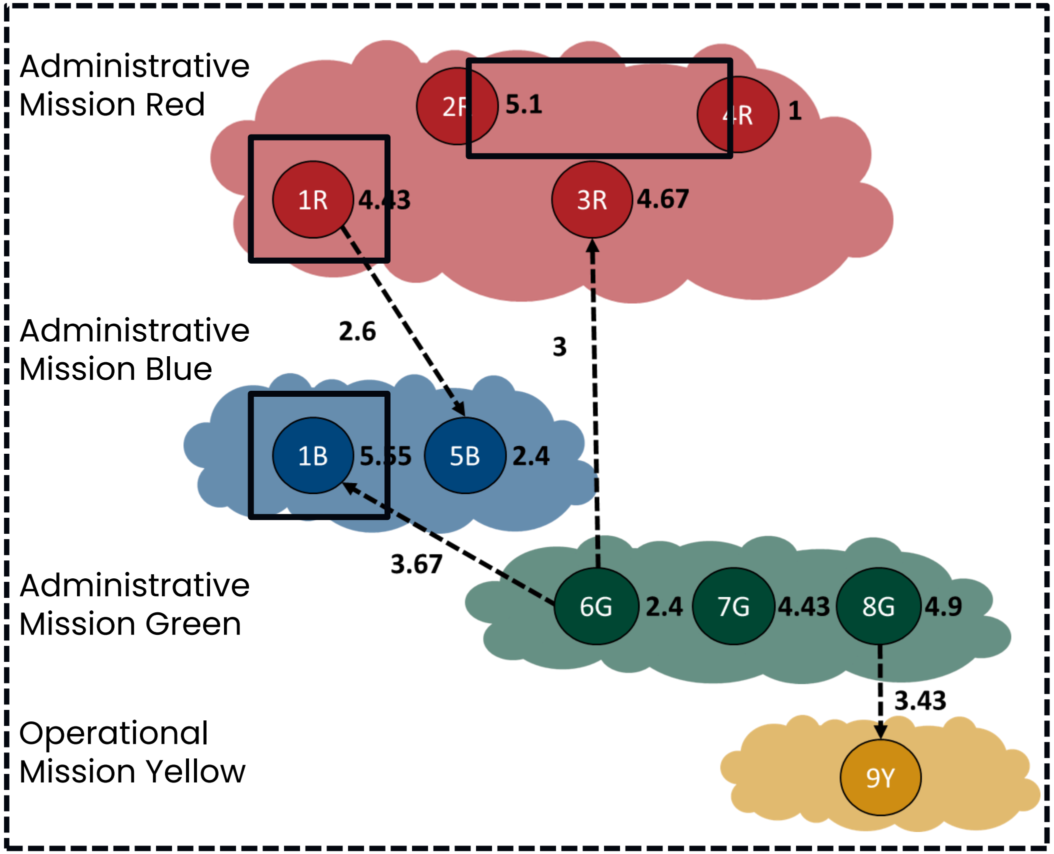

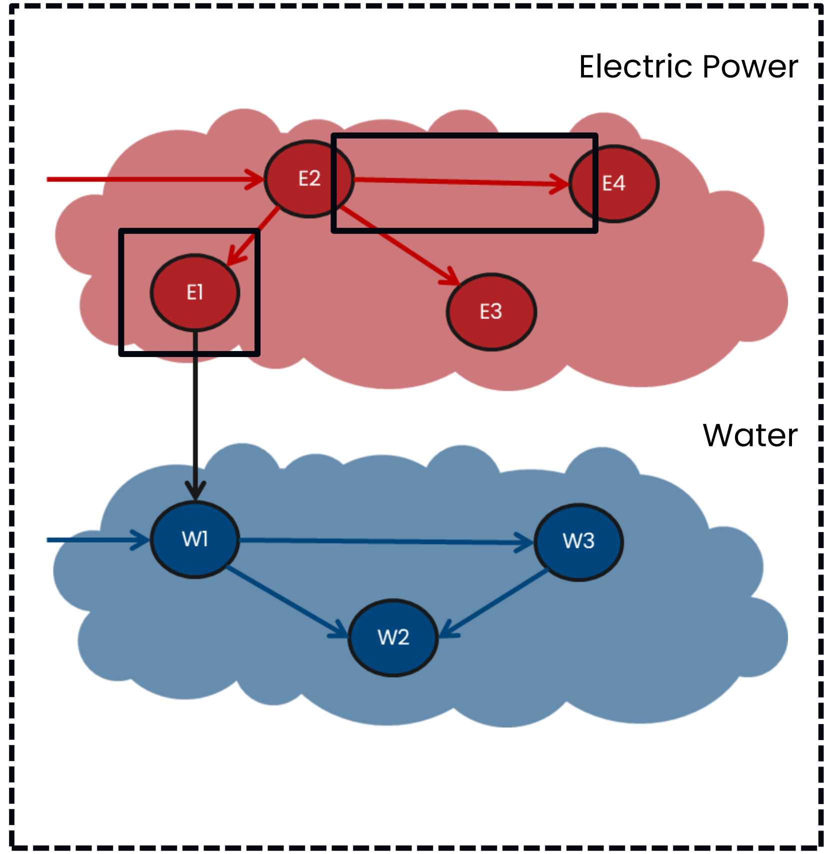

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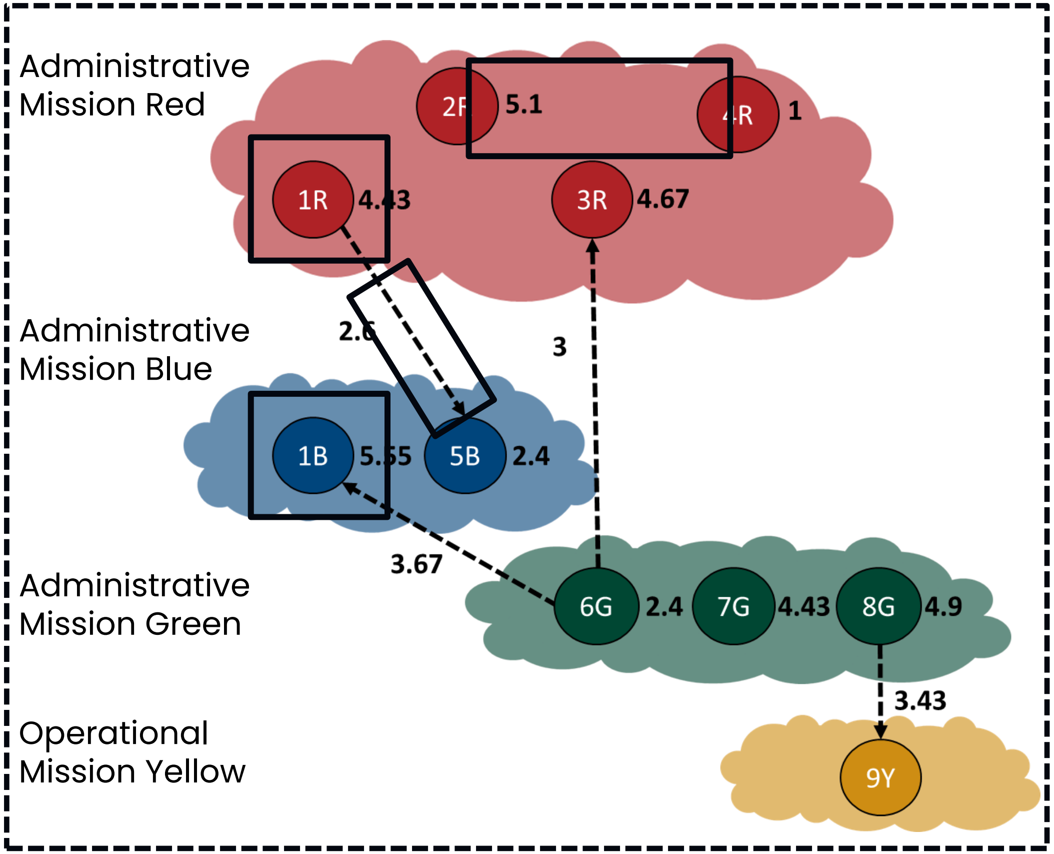
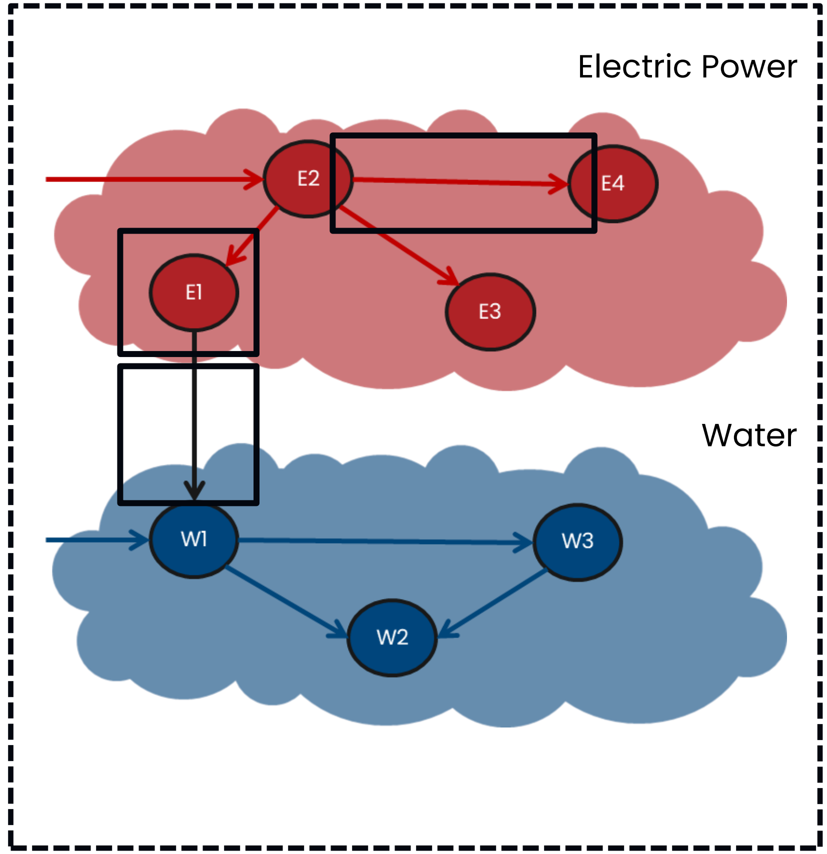
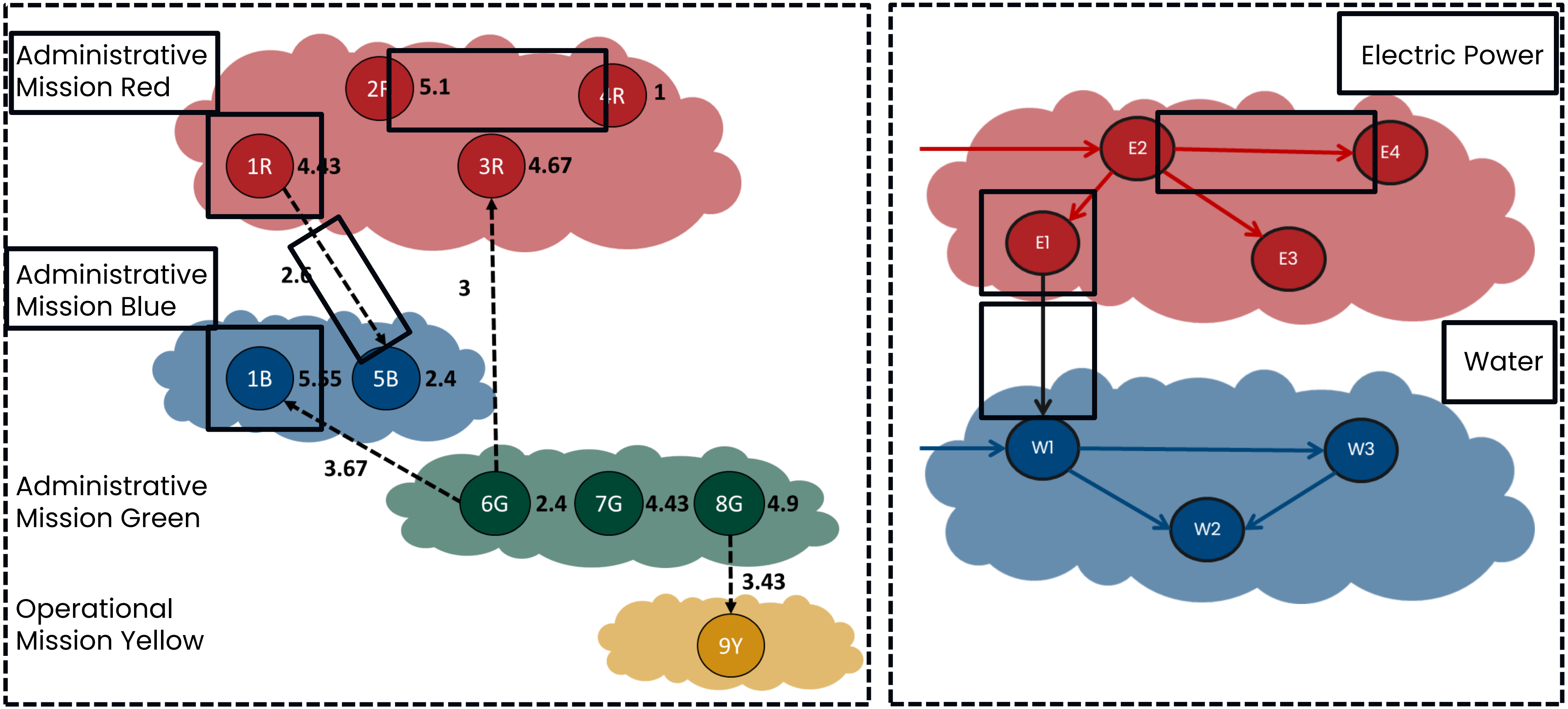


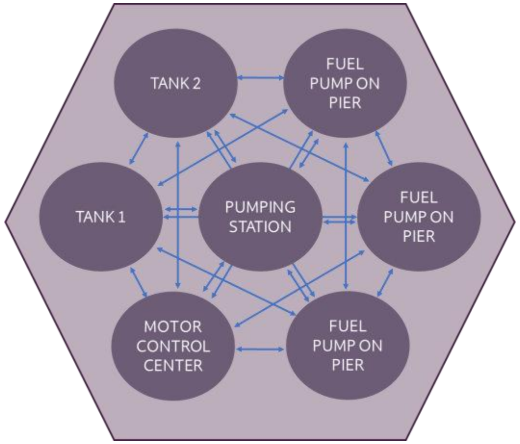


MDI as a Multilayer Network (LCDR Fish 2021)

Comparing Systems… Lots of Problems!



Realistic, but Fictitious Diesel Fuel Marine Mission



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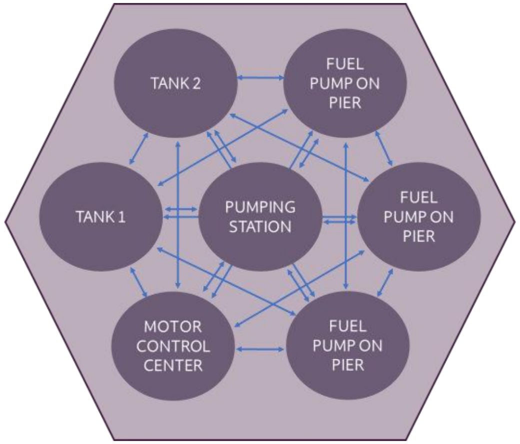

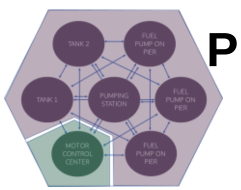
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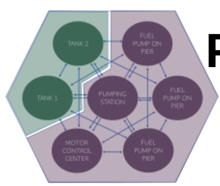
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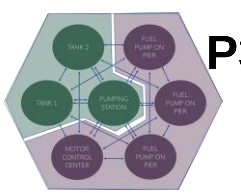
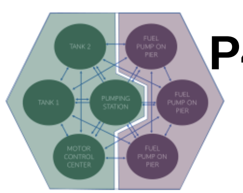
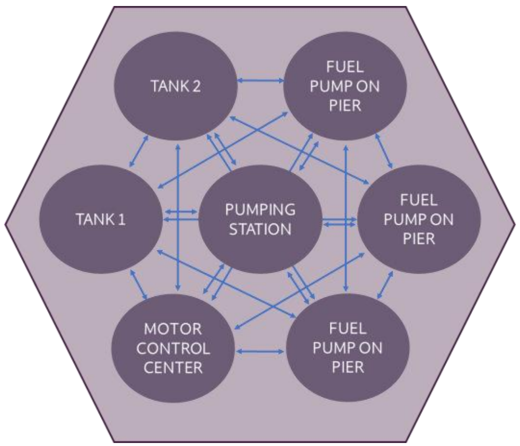
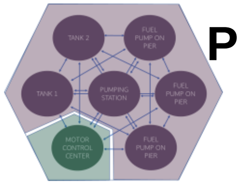

P3

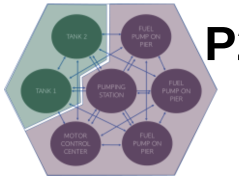

P4

Realistic, but Fictitious Diesel Fuel Marine Mission





P1



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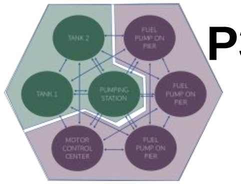

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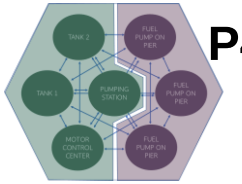
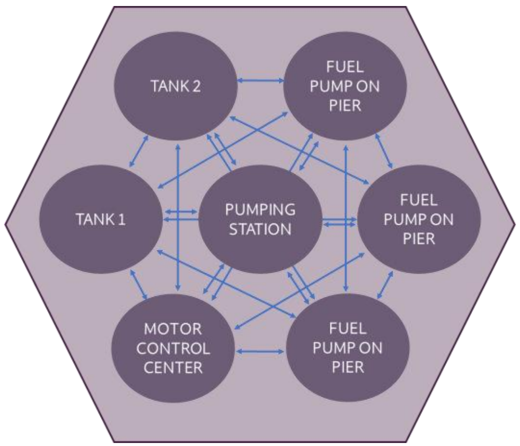


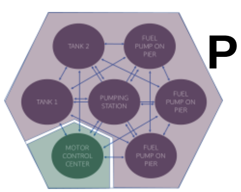
P4

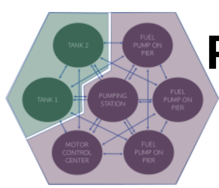
Partition	$\lvert M_1 \rvert$	$\lvert M_2 \rvert$	M_1 MDI	M_2 MDI
P0	0	7	N/A	65.55
P1	1	6	69.8	66.9
P2	2	5	69.3	68.0
P3	3	4	69.2	68.7
P4	4	3	68.7	69.2

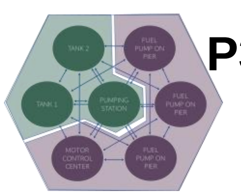
Significant (84-70) **Relevant (69-55)**

Realistic, but Fictitious Diesel Fuel Marine Mission




P1


P2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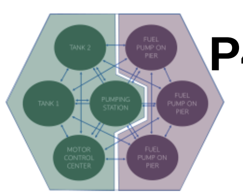
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Significant (84-70) **Relevant (69-55)**

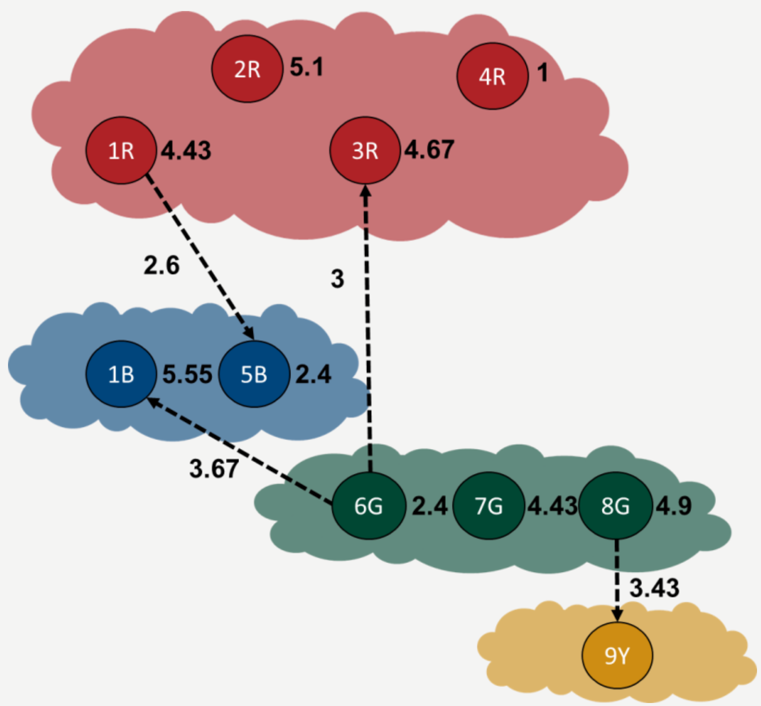
By Analyzing MDI, We Find Flaws and Solutions

- **MDI is sensitive to the size and composition of missions**
- Can lead to **ineffective scoring and bad prioritization**
- Large **ramifications for Navy infrastructure decisions**

Realistic, but Fictitious
Diesel Fuel Marine

Partition	IMI	IM I	M MDI	M MDI

Results Presented to NAVFAC Civil Engineering Corps



"…directly supporting NAVFAC's ability to deliver technical and acquisition solutions for the fleet **with** world-class **research** and education **on** analyzing and **improving vulnerability analysis and Mission Dependency Index**… …**we are** actively **working to bring their** tools, education and **insight to the entire NAVFAC enterprise** and Civil Engineer Corps

– CDR Ed Fosson, XO (former), Center for Seabees and Facilities Engineering

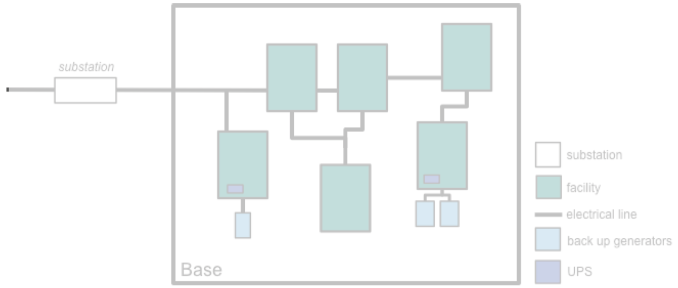
Eisenberg, Daniel A., Aaron B. Fish, and David L. Alderson. "What is wrong with the Mission Dependency Index for US federal infrastructure decisions?." *Risk Analysis* (2022).

infrastructure decisions

Research Inside & Outside the Fence Line

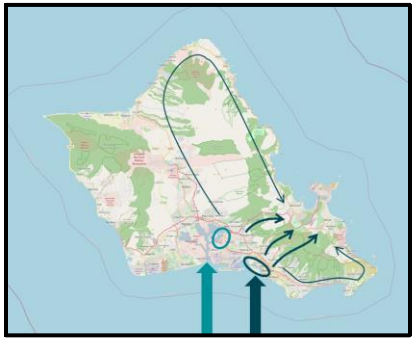
Inside the Fence Line

- Is there a framework for interdependent infrastructure modeling & analysis useful for installation vulnerability?
- How does the DoD relate infrastructure to mission?
- How is the DoD currently prioritizing their own infrastructure? Is it sufficient?



Outside the Fence Line

- How do community needs and infrastructure systems impact mission?
- How to better coordinate military installations and local communities during disasters?
- What investments outside the fence line support resilience?



Critical Infrastructure Resilience Collaboration & Assessment (CIRCA)

Objective: Improve the resilience of military installations to extreme events. Installation resilience is tied to their local communities, including shared critical infrastructure systems and resources.

Project Benefits:

- **Fully-funded & managed** project. Funded by OSD SERDP Program. NPS and CSL coordinate analysis.
- **Stakeholder-driven analysis** supports local installation and community needs.
- **Achieve mission and community resilience** through models that support planning and funding decisions.

Naval Station Newport

*Fictionalized depiction of Newport infrastructure.

MCBH Kāne'ohe Bay

*Fictionalized depiction of K-Bay infrastructure.

NAVSTA Newport (LCDR Jones 2021)

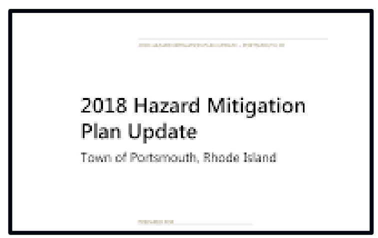
One Island, 5 Communities:

- **NAVSTA Newport vulnerable to sea level rise and coastal flooding.**
- Newport City, Middletown, and Portsmouth **each produce separate evacuation plans.**
- **NAVSTA Newport evacuation plans end at the fenceline.**

Concerns:

- Plans do not consider climate change
- Limited integration, each plan uses the same shelters and routes
- Limited coordination

Goal: evacuation planning for future storms

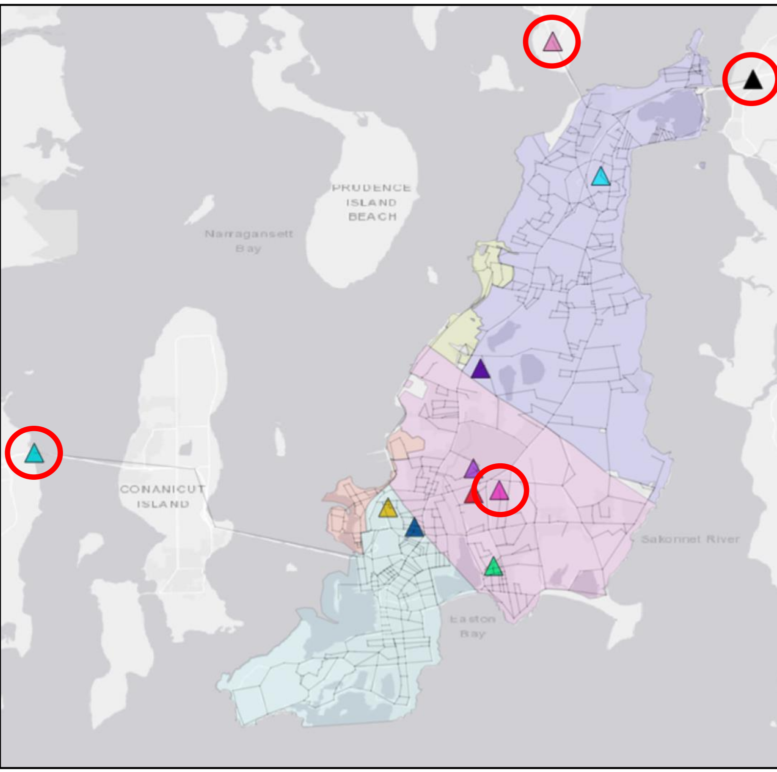


ID	Event Type	Sea Level
1	Calm- No Storm	Present MSL (reference)
2		1 ft SLR
3		3 ft SLR
4		5 ft SLR
5	High Impact Hurricane using modified track to maximize storm surge (modification of 1938 Great New England Hurricane)	Present MSL (reference)
6		1 ft SLR
7		3 ft SLR
8		5 ft SLR
9	Hybrid Storm – Superstorm Sandy	Present MSL (reference)
10		1 ft SLR
11		3 ft SLR
12		5 ft SLR

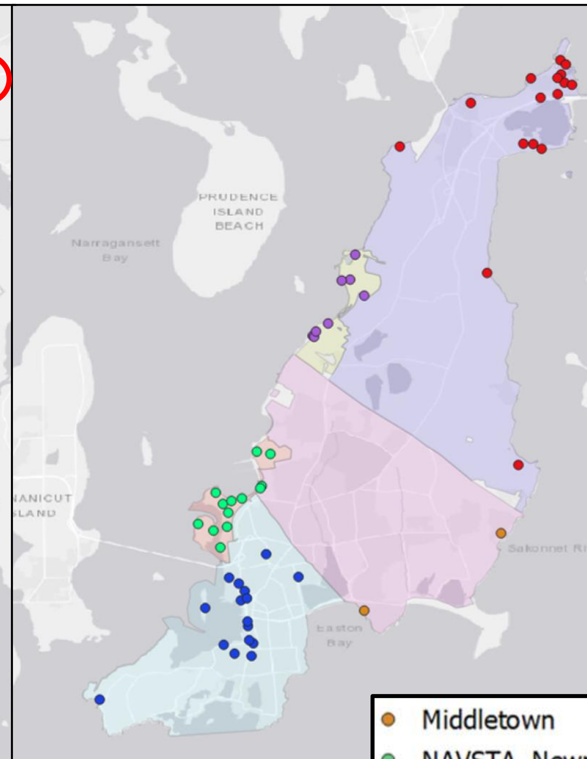
MSL: Mean Sea Level SLR: Sea Level Rise

NAVSTA Newport (LCDR Jones 2021)

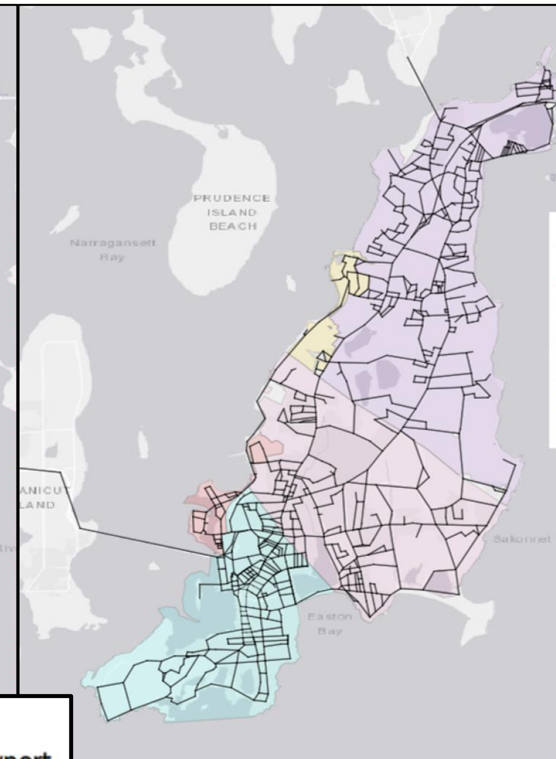
Shelters and Off-Island Evacuation



At-risk Populations



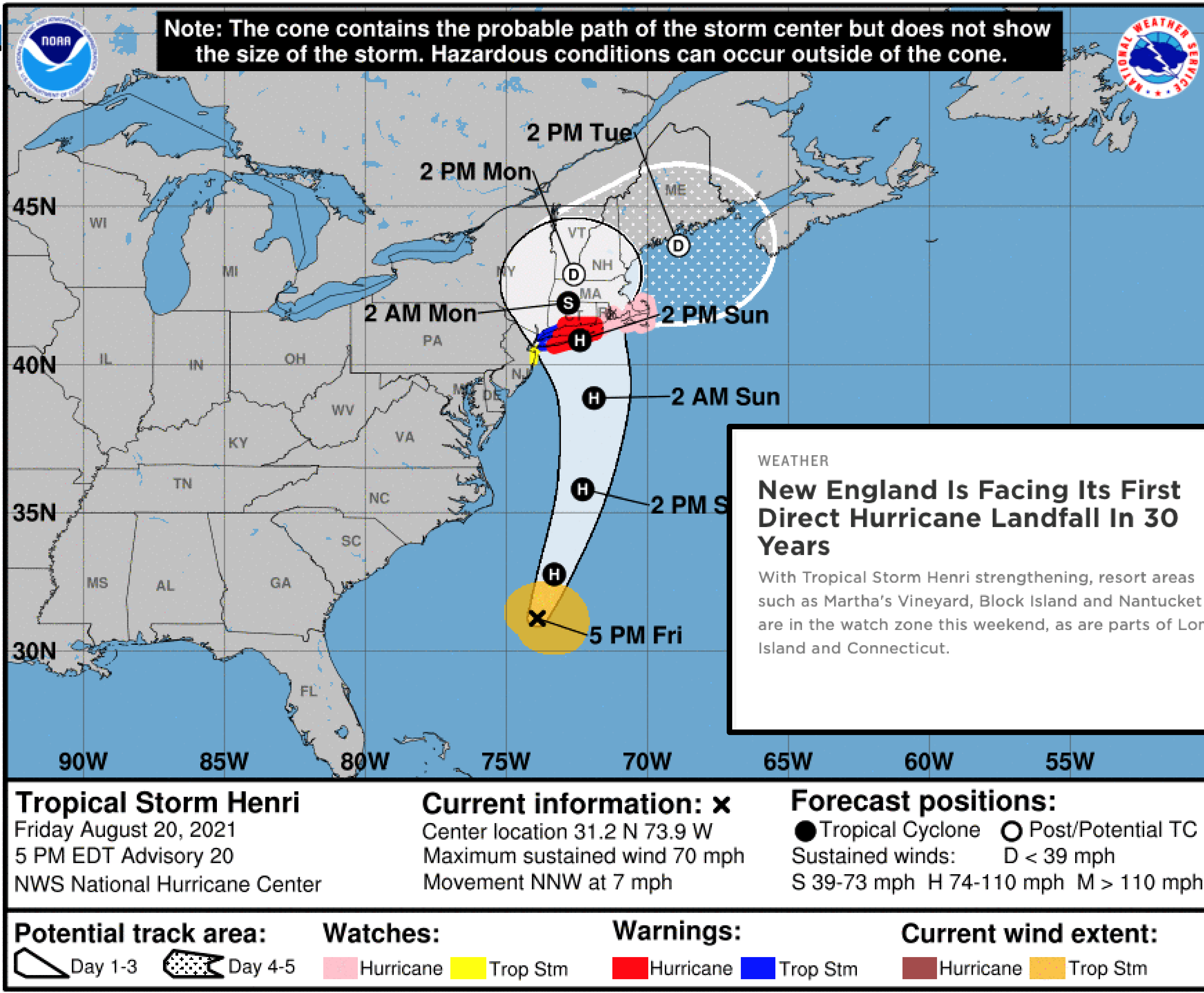
Road Network



Evac Destinations

- 3 Bridges
- One shelter

Vulnerable populations across all communities

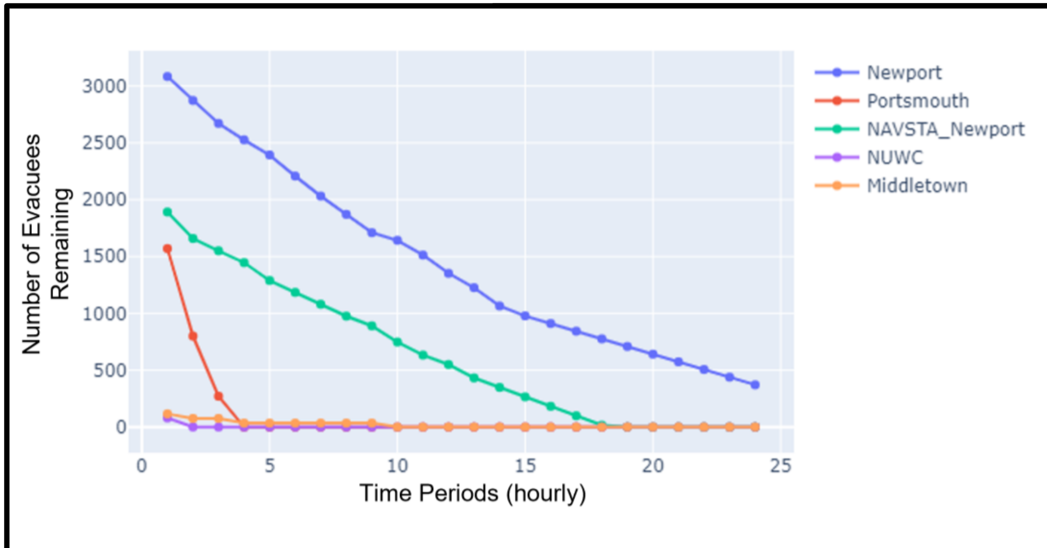


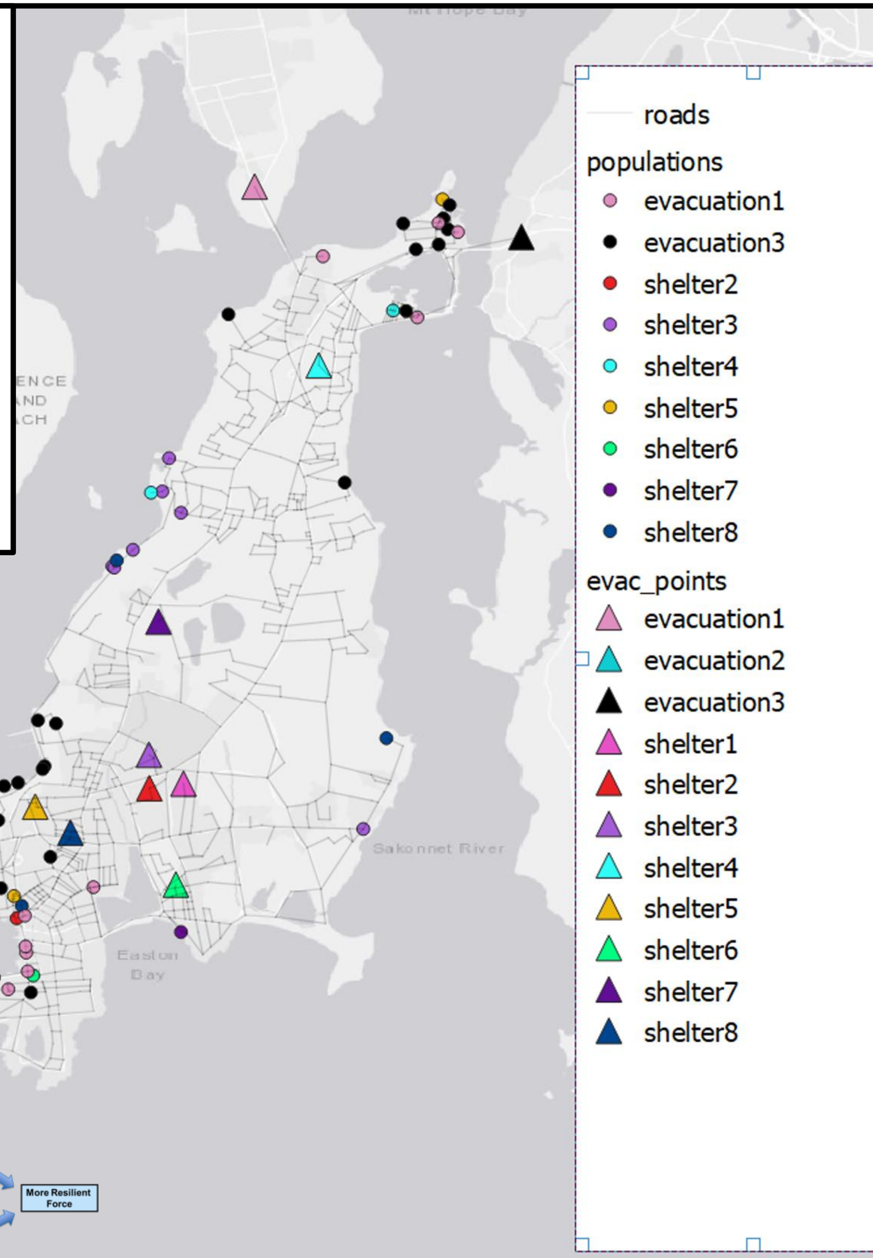
WEATHER

New England Is Facing Its First Direct Hurricane Landfall In 30 Years

With Tropical Storm Henri strengthening, resort areas such as Martha's Vineyard, Block Island and Nantucket are in the watch zone this weekend, as are parts of Long Island and Connecticut.

NAVSTA Newport (LCDR Jones 2021)





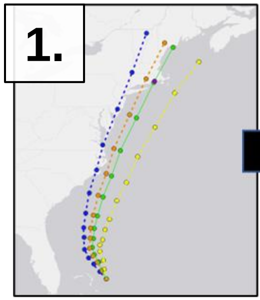
Hurricane Henri:

- 19 Hours to full evacuation of NAVSTA Newport
- Military personnel sent off-island to free up shelters

NAVSTA Newport (ENS Domanowski 2022)

Synthetic Storm Generation → **Uncertain Evacuation Demand + Routing**

1.



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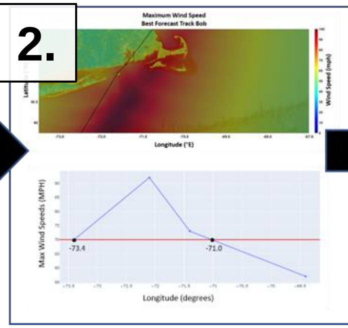

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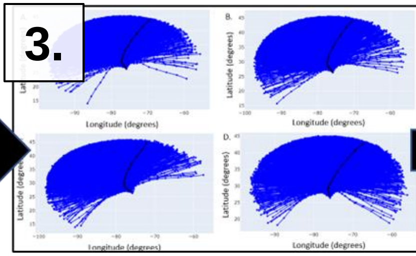


4.

$$D_{s,\tau+1} = Veh(D_{s,\tau}) * hit(\tau) * C(\tau)$$

$$Veh(D_{s\tau}) = z_s - \sum_{\tau} D_{s\tau}$$

$$hit(\tau) = \begin{cases} 0, & \text{if } \phi_\tau < \phi_c \\ \phi_\tau, & \text{otherwise} \end{cases}$$

$$C(\tau) = \begin{cases} 0, & \text{if } \tau < \tau_b^c \\ 1, & \text{if } \tau_b^c \le \tau \le \tau_a^c \\ 0, & \text{if } \tau > \tau_a^c \end{cases}$$

5.

$$\min_{\sigma,\beta,\mu} \sum_s \sum_\tau \mu_{s\tau} \tag{3.6}$$

$$\text{s.t.} \sum_s \sum_k \beta_{s\tau k} w_{sijk} \le \left(\frac{60 \cdot d_{ij\tau}}{\rho_{ij\tau}} c_{ij\tau}\right) \quad \forall (i,j) \in A, \forall \tau \in T \tag{3.7}$$

$$\sum_k \sigma_{sk} = 1 \quad \forall s \in S \tag{3.8}$$

$$\sum_\tau \beta_{s\tau k} \le \sigma_{sk} z_s \quad \forall s \in S, \forall k \in K_s \tag{3.9}$$

$$\mu_{s0} = D_{s0} \quad \forall s \in S \tag{3.10}$$

$$\mu_{s,\tau+1} = \mu_{s\tau} - \sum_k \beta_{s\tau k} + D_{s\tau} \quad \forall s \in S, \forall \tau \in T-1 \tag{3.11}$$

$$\sum_s z_s \left[\sum_k \sigma_{sk} \lambda_{sek}\right] \le v_e \quad \forall e \in E \tag{3.12}$$

$$\sigma_{sk} \in \{0,1\} \quad \forall s \in S, k \in K_s \tag{3.13}$$

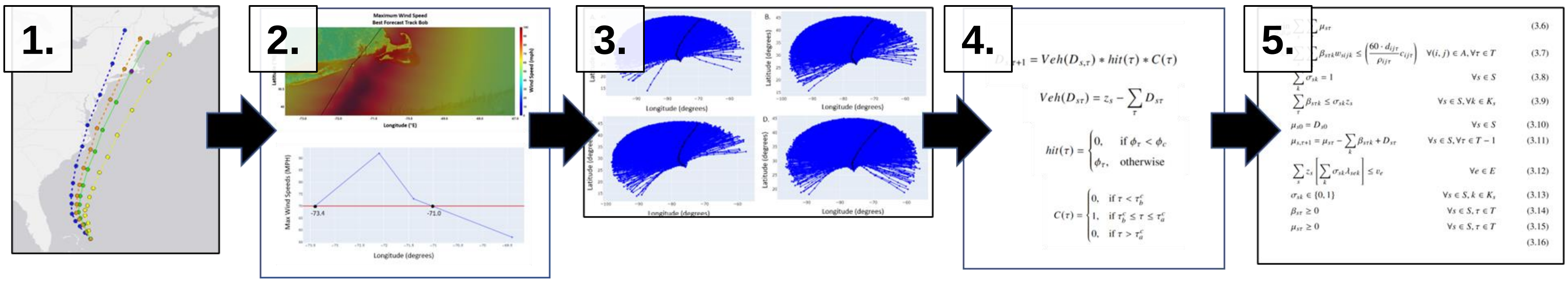
$$\beta_{s\tau} \ge 0 \quad \forall s \in S, \tau \in T \tag{3.14}$$

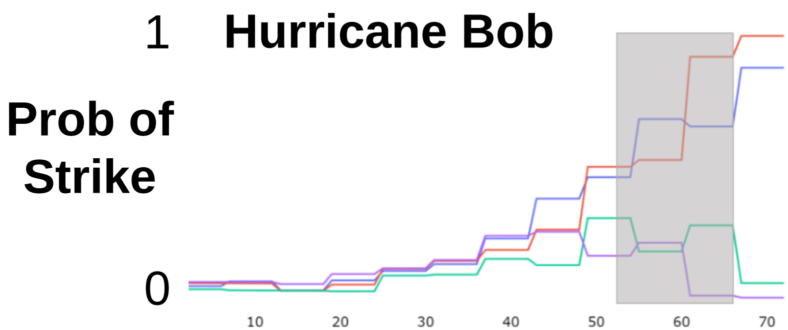
$$\mu_{s\tau} \ge 0 \quad \forall s \in S, \tau \in T \tag{3.15}$$

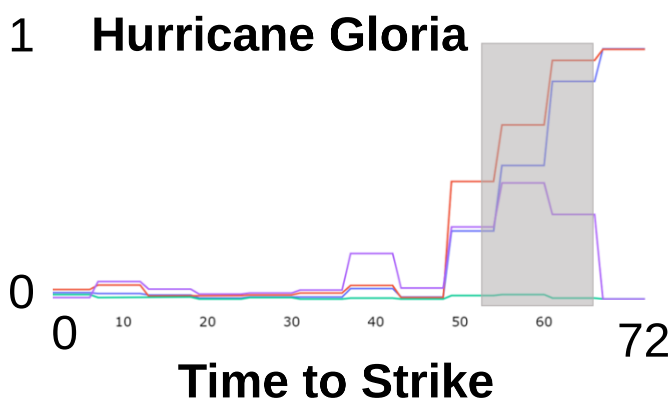
(3.16)

NAVSTA Newport (ENS Domanowski 2022)

Synthetic Storm Generation → **Uncertain Evacuation Demand + Routing**

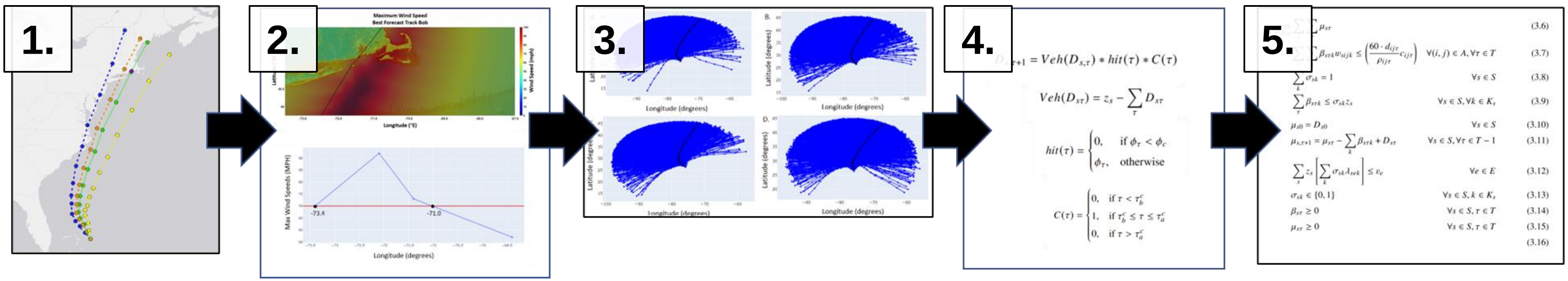


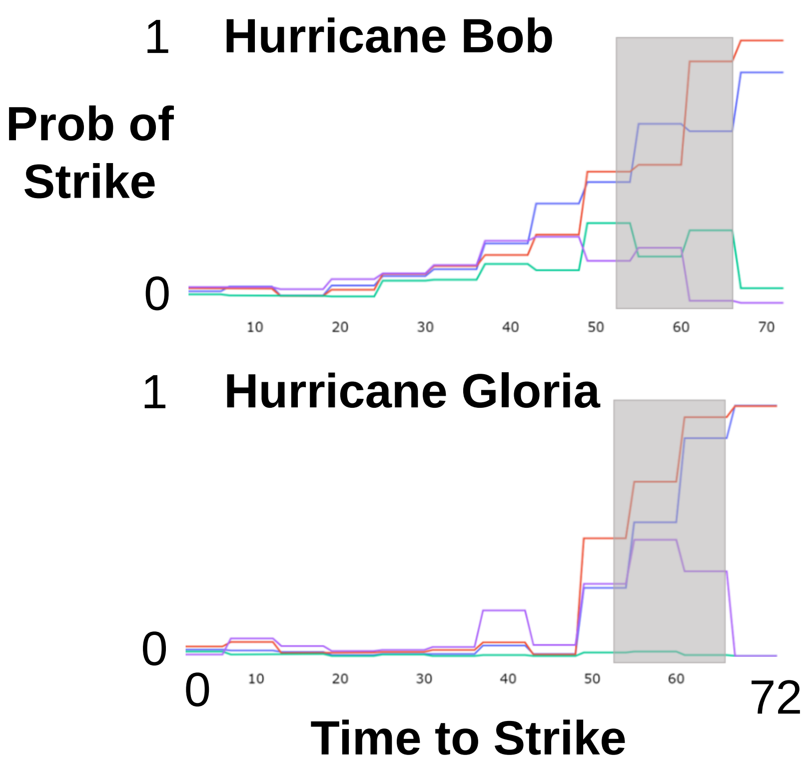




NAVSTA Newport (ENS Domanowski 2022)

Synthetic Storm Generation → Uncertain Evacuation Demand + Routing





Evacuation Across All Scenarios

Track	Bob Total Evacuated	Bob Total Not Evacuated	Gloria Total Evacuated	Gloria Total Not Evacuated
Original	6985	-	6985	-
Worst-Case	6985	-	6903	82
180°	6431	554	945	6040
90°	5808	1177	6950	35

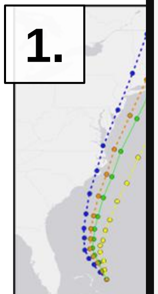
The maximum number of vehicles that can evacuate is 6,985.

- Current **results are too conservative**
- Model provides a **basis for future evacuation coordination** and routing

NAVSTA Newport (ENS Domanowski 2022)

Synthetic Storm Generation → **Uncertain Evacuation Demand + Routing**

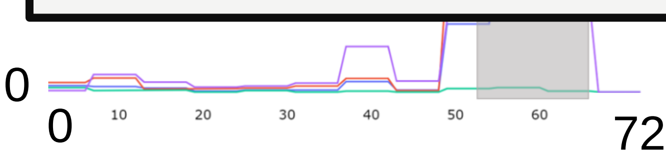
1.



Prob of Strike

Results Used for Installation Decision-Making

- Results **briefed to Admiral in charge of Hurricane Henri** emergency response
- **Used in TTX** to develop military installation resilience review (MIRR)
- **Briefed to local emergency managers**
- **Briefed to political leaders & decision makers**



Time to Strike

evacuation coordination and routing

SERDP
DOD • EPA • DOE

Marine Corps Base Hawaii Last-Mile Supplies

DoD and Federal	State and Local	Private, NGO, Uni

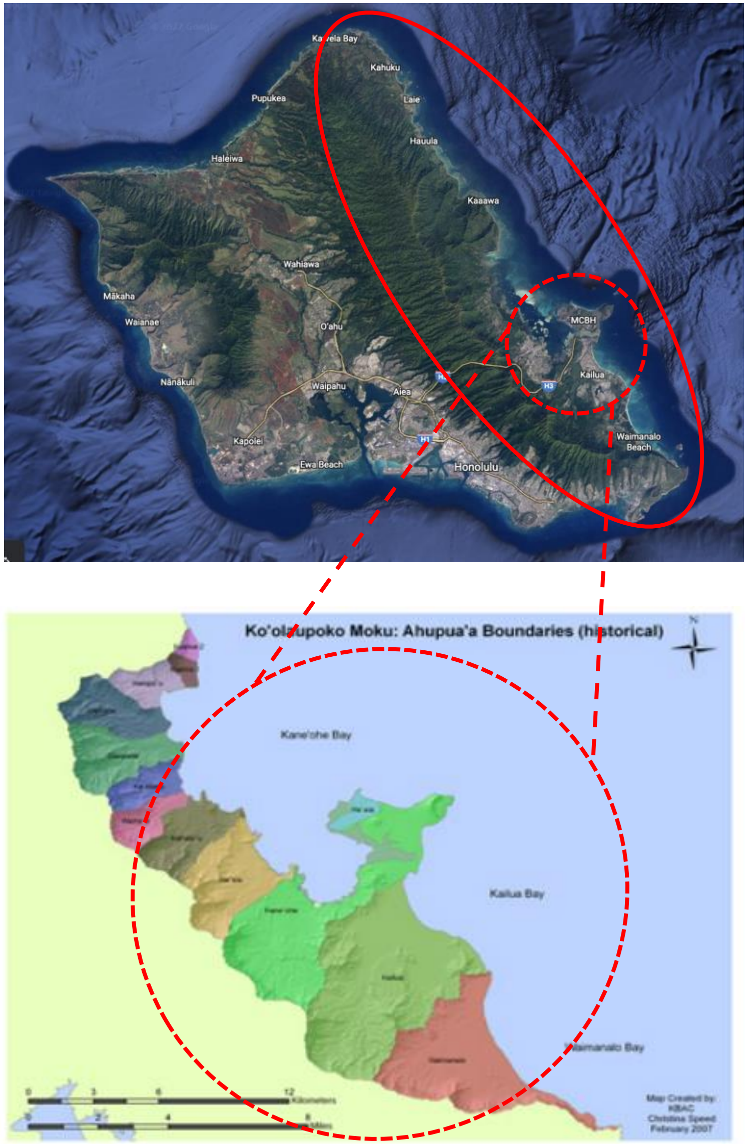
Problem: Last-mile distribution requires analysis and integration.

- Oahu does not have a Coordinated Community Point of Distribution (POD) plan.
- Need coordination for pre-, during, and post-disaster response.

Coordination with Key Stakeholders

- Federal >> Local Decision-makers and planners.
- Inclusion of key private stakeholders, e.g., Hawaii Foodservice Alliance, Pacific Disaster Center.
- Food and disaster management experts at UH.

Marine Corps Base Hawaii Last-Mile Supplies



Windward Oahu & Marine Corps Base Hawaii (MCBH)

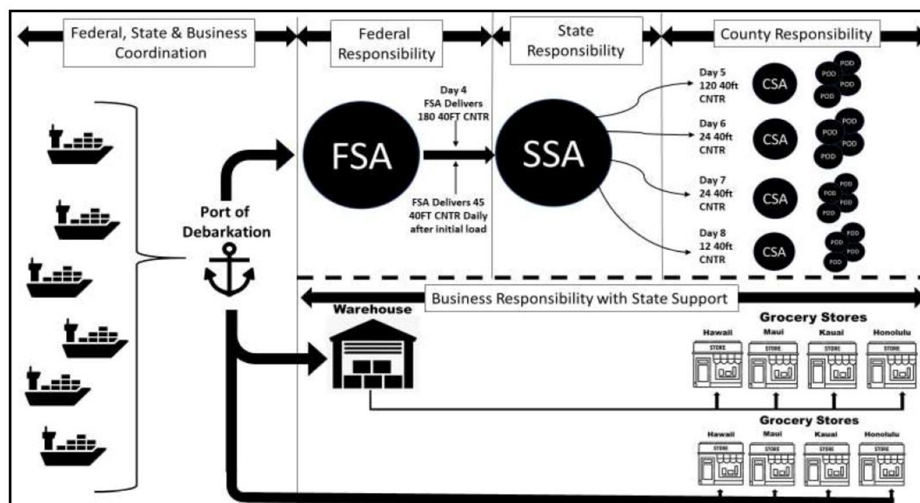
- Population (2020): 137,115 (~10%)
- 2 military bases: MCBH + Bellows
- Isolated by mountains
- 48% of military + civilian staff live off the installation

Marine Corps Base Hawaii Last-Mile Supplies

Windward Oahu & Marine Corps Base Hawaii (MCBH)

- Population (2020): 137,115 (~10%)
- 2 military bases: MCBH + Bellows
- Isolated by mountains
- 48% of military + civilian staff live off the installation

Distribution Management Plan Lacks Coordination & Implementation



Marine Corps Base Hawaii Last-Mile Supplies

Goal: Identify best locations for pre-covery and resupply PODs.

Pre-covery PODs: Preposition food and water before disaster (shown right).

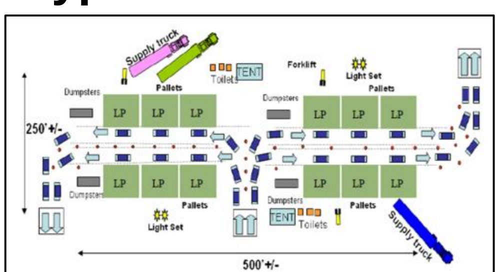
- **Feed more** people with **less space**.
- Require **long-term storage and maintenance**. Have more requirements.

Image of HFA Pre-covery POD

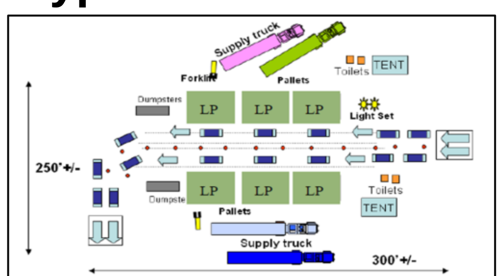
Resupply PODs: Post-disaster resupply.

- Limited to FEMA standard layouts (shown below).

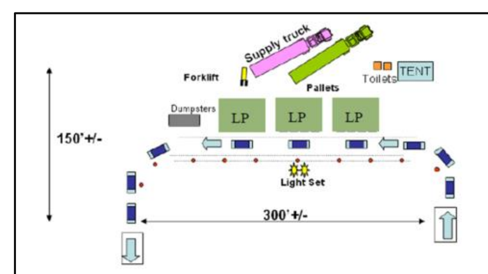
Type 1: 20k meals



Type 2: 10k meals



Type 3: 5k meals



POD Location-Allocation (Husemann, Wigal)

Data: Key Roads, Populations (2020 Census), and *Possible* PODs

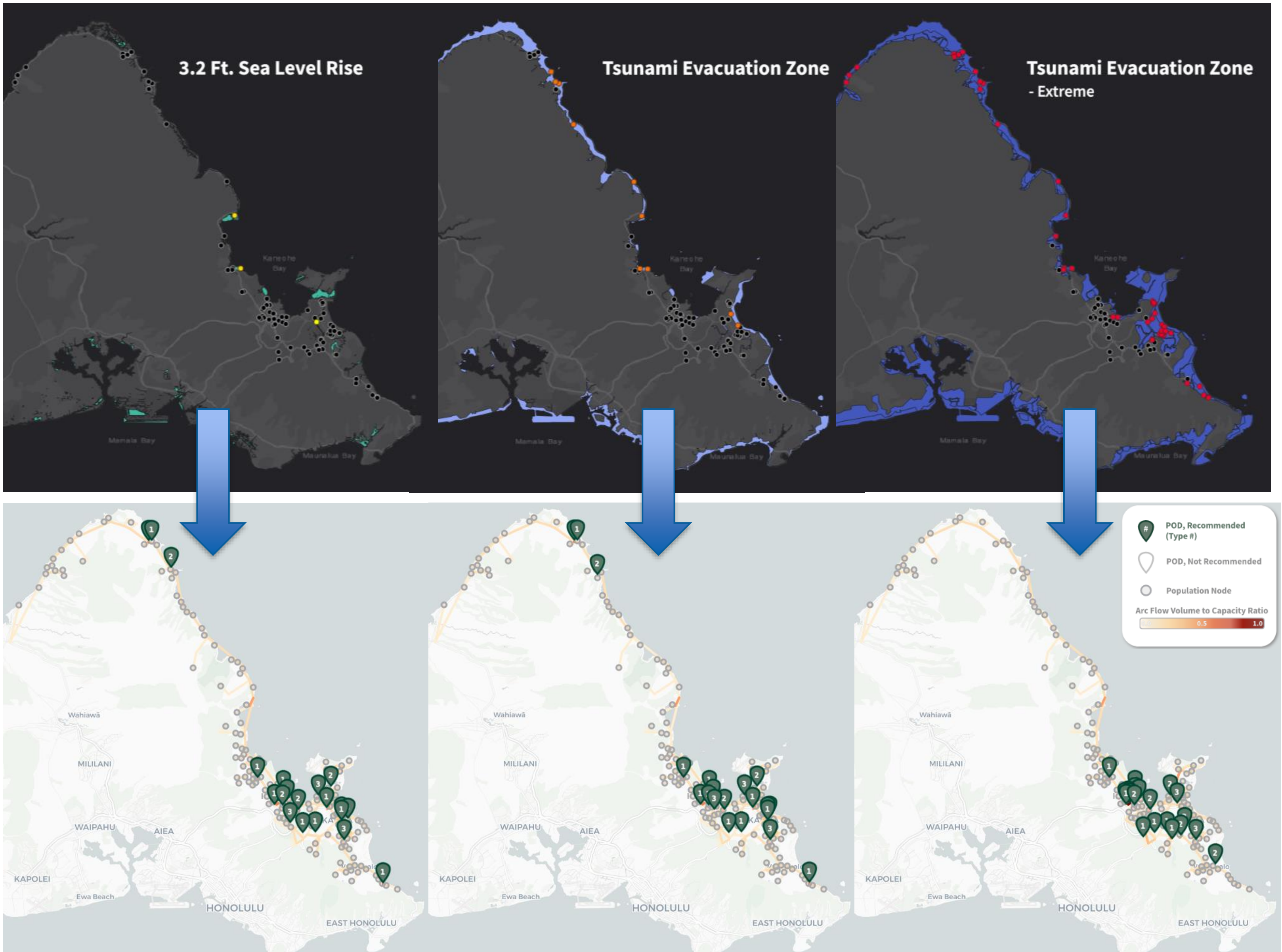
Model-based Recommendations

- **Data** developed **to determine POD locations** across entire island.
- **Model traffic** and congestion across Windward Oahu **to determine optimal** Windward **POD locations.**

POD Location-Allocation (Husemann, Wigal)

Hazards

Results



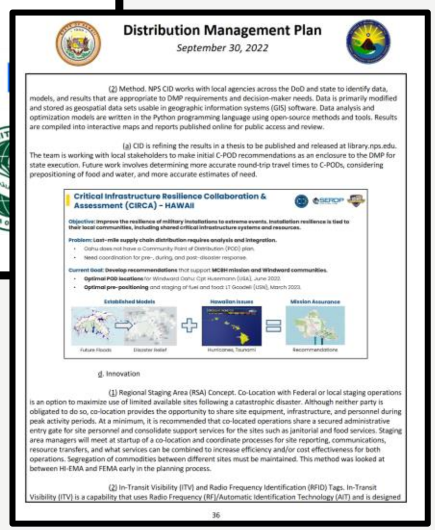
http://faculty.nps.edu/cid/pods/inundation_update.html

POD Location-Allocation (Husemann, Wigal)

Hazards

Briefed to Federal, State, Local, and DoD Stakeholders Incorporated into State Plans

Coordination for Emergency Distribution



Distribution Management Plan

September 30, 2022

(2) Method. NPS CID works with local agencies across the DoD and state to identify data, models, and results that are appropriate to DMP requirements and decision-maker needs. Data is primarily modified and stored as geospatial data sets usable in geographic information systems (GIS) software. Data analysis and optimization models are written in the Python programming language using open-source methods and tools. Results are compiled into interactive maps and reports published online for public access and review.

(a) CID is refining the results in a thesis to be published and released at library.nps.edu. The team is working with local stakeholders to make initial C-POD recommendations as an enclosure to the DMP for state execution. Future work involves determining more accurate round-trip travel times to C-PODs, considering prepositioning of food and water, and more accurate estimates of need.

Critical Infrastructure Resilience Collaboration & Assessment (CIRCA) - HAWAII

Objective: Improve the resilience of military installations to extreme events. Installation resilience is tied to their local communities, including shared critical infrastructure systems and resources.

Problem: Last-mile supply chain distribution requires analysis and integration.

- Oahu does not have a Community Point of Distribution (POD) plan.
- Need coordination for pre-, during, and post-disaster response.

Current Goal: Develop recommendations that support MCBH mission and Windward communities.

- Optimal POD locations for Windward Oahu: Cpt Husemann (USA), June 2022.
- Optimal pre-positioning and staging of fuel and food: LT Goodell (USN), March 2023.

Established Models | Hawaiian Issues | Mission Assurance

Future Floods | Disaster Relief | Hurricanes, Tsunami | Recommendations

d. Innovation

(1) Regional Staging Area (RSA) Concept. Co-Location with Federal or local staging operations is an option to maximize use of limited available sites following a catastrophic disaster. Although neither party is obligated to do so, co-location provides the opportunity to share site equipment, infrastructure, and personnel during peak activity periods. At a minimum, it is recommended that co-located operations share a secured administrative entry gate for site personnel and consolidate support services for the sites such as janitorial and food services. Staging area managers will meet at startup of a co-location and coordinate processes for site reporting, communications, resource transfers, and what services can be combined to increase efficiency and/or cost effectiveness for both operations. Segregation of commodities between different sites must be maintained. This method was looked at between HI-EMA and FEMA early in the planning process.

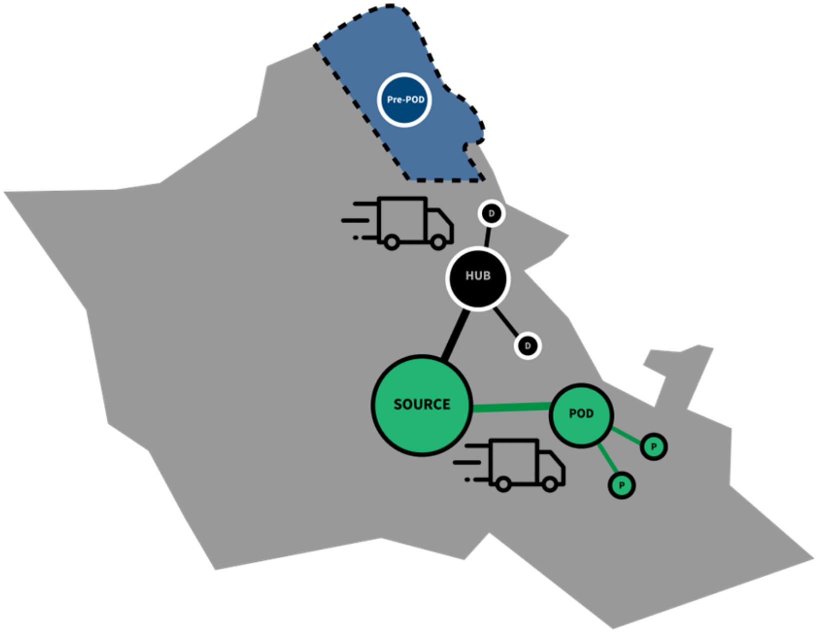
(2) In-Transit Visibility (ITV) and Radio Frequency Identification (RFID) Tags. In-Transit Visibility (ITV) is a capability that uses Radio Frequency (RF)/Automatic Identification Technology (AIT) and is designed

36

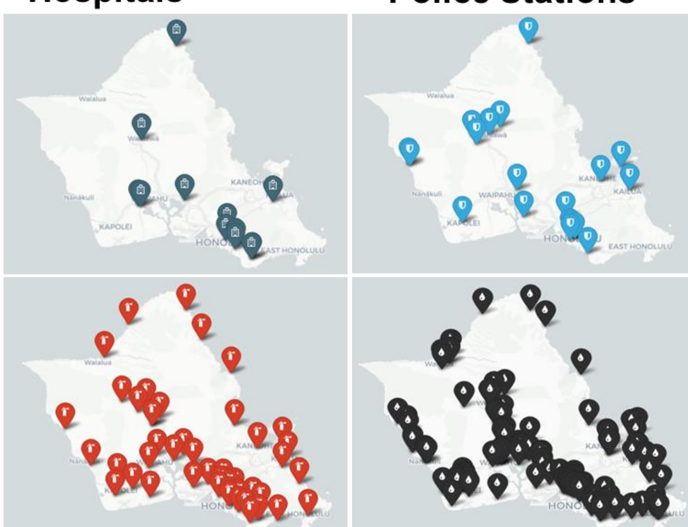
- Results guiding project development for emergency management infrastructure (DCIP)
- Adopted by state emergency management agency
- MCBH CO interested in applying methods across pacific

Results

Next Steps: Hybrid (Wigal), Fuel (Goodell)



Hospitals | Police Stations



Fire Stations | Gas Stations

Hybrid Concept: Combining pre-covery, FEMA ops, and delivery

- Hybrid approach needed to serve vulnerable populations.
- **Where should PODs be if some drivers used for delivery?**

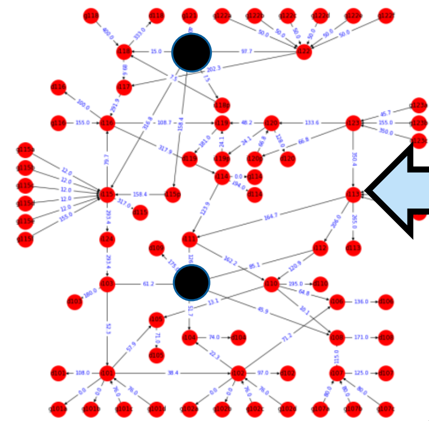
Towards Interdependent Systems:

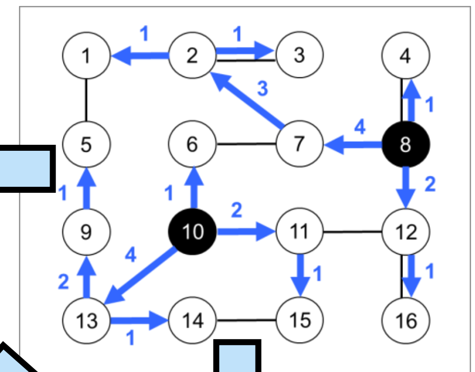
- Refueling combines roads with pipelines
- **Develop optimal refueling strategy.**
- **Future:** Interdependent network vulnerability analysis

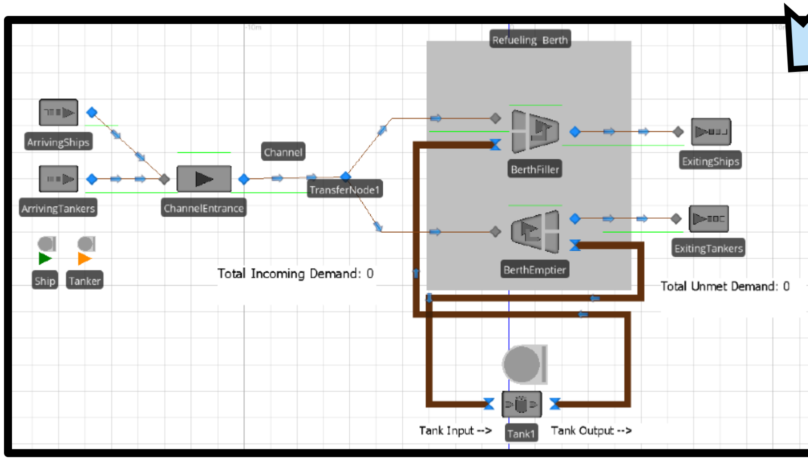
Next Steps: Integrating Methods

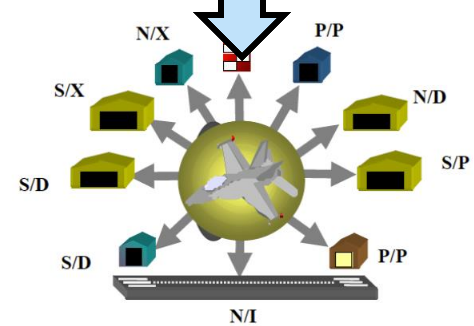
Advance Methods for Worst-Case Failure Models:

- Fuel & Food for MCBH
- Worst-case Modeling in collaboration with NICE project: Ganguly (NEU), Chatterjee (PNNL)









Summary

- **Research Advances Models and Methods in the DoD**
  - Interdependent network flow optimization + rapid model development
  - MDI flaws and solutions
- **Work directly impacting Navy and Marine Corps Installations**
  - NAVFAC CEC Community trained with MDI analysis
  - Evacuation Planning for Naval Station Newport + Aquidneck Island
  - Last-Mile Supply Chain Resilience for Marine Corps Base Hawaii
- **Coordinating with Climate Change + Defense Communities**
  - NPS Climate & Security Network (CSN)
  - Resource Competition, Environmental Security, and Stability (RECESS)
  - Intel Community Environmental Research Working Group (ICESWG)

Thank You!

- Dr. Daniel Eisenberg

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Assistant Professor, Operations Research
Naval Postgraduate School
daniel.eisenberg@nps.edu
http://faculty.nps.edu/deisenberg

- NPS Center for Infrastructure Defense

http://www.nps.edu/cid

- Related Links and Maps

faculty.nps.edu/cid/pods/inundation_update.html

Publications

Published:

- Kuc, Matthias P. "A Computational Framework for Optimization-based Interdependent Infrastructure Analysis and Vulnerability." Master’s in Operations Research, Naval Postgraduate School, 2020.
- Fish, Aaron B. “Overcoming Flaws in the Mission Dependency Index with Network Flow Analysis." Master’s in Operations Research, Naval Postgraduate School, 2021.
- Pulliam, Daniel B. “Developing a framework for analyzing the resilience of forward expeditionary port refueling infrastructure." Master’s in Operations Research, Naval Postgraduate School, 2021.
- Herster-Dudley, Marci, “Building resilience in DoD Microgrids by considering human factors in recovery procedures,” Master’s in Systems Engineering, Naval Postgraduate School, 2021.
- Jones, Amanda, “Mission-informed evacuation models for Naval Station Newport and Aquidneck Island,” Master’s in Operations Research, Naval Postgraduate School, 2021.

Publications (cont.)

Published:

- Eisenberg, DA, Fish, AB, Alderson, DL, “What’s wrong with the Mission Dependency Index for U.S. Federal Infrastructure Decisions?” *Risk Analysis*, (2022)
- Husemann, Tate, “Last-Mile Supply Chain Resilience for Marine Corps Base Hawaii,” June 2022
- Domanowski, Christina, “Robust Evacuation Plans for Naval Station Newport and Aquidneck Island,” June 2022

In-Preparation:

- Wigal, Jacob, “Optimizing Last Mile Delivery of Disaster Relief Supplies for Oahu, Haii” Expected March 2023
- Goodell, Felicia, “Last Mile Refueling for Oahu and Marine Corps Base Hawaii ” Expected March 2023
- Eisenberg et al., “Methods for Interdependent Infrastructure Model Fusion,” in-prepartion

BACKUP SLIDES

RC20-1091: Modeling Compound Threats to Interdependent Infrastructure on Military Installations

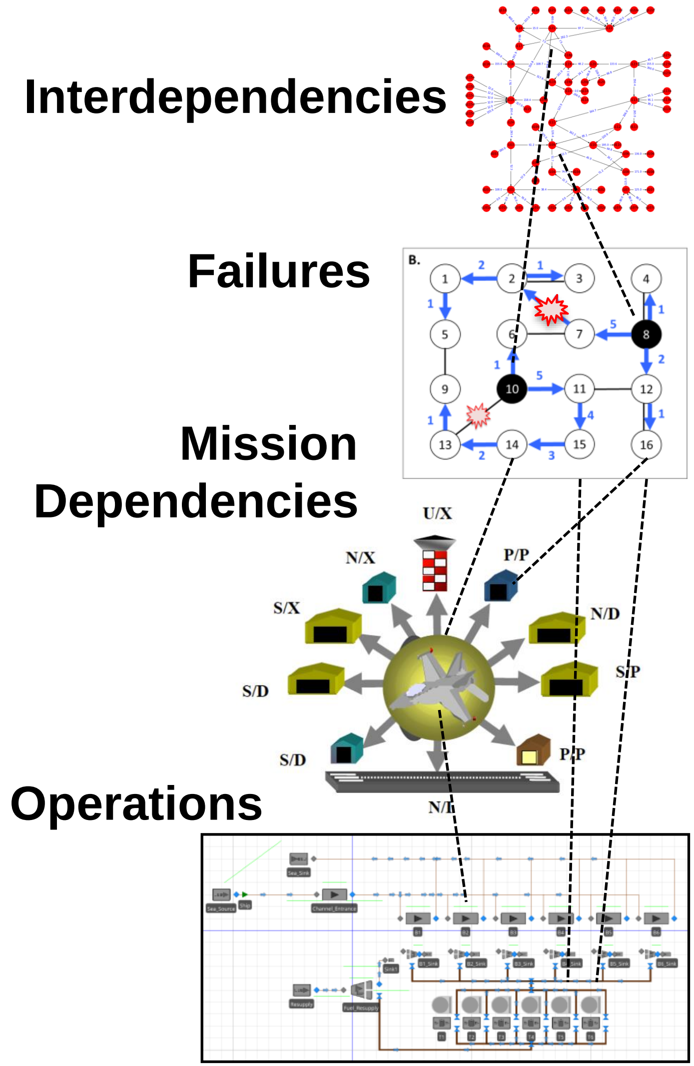
Performers:
- **NPS:** Daniel Eisenberg, David Alderson
- **Contractors:** Converge Strategies, LLC

Research Focus
- Develop a method to map installation and facility vulnerabilities to compound threats (SON 2).
- Assess how to improve resilience without specifying threats (SON 3).

Research Objectives
- Create methods to assess worst-case disruptions to interdependent infrastructure on installations
- Link infrastructure mission to investment

Project Progress and Results
- 9 Master’s Theses Completed
- Active Case Studies with Multiple Installations

Technology Transition
- Students → Fleet
- NAVFAC, NAVSTA Newport, MCBH



Technical Approach: Worst-Case Failures

- One player is trying to ensure the “operation” of a system.

  We call this player the *operator* or *defender*.
- Another player is trying to *interdict* that operation.

  We call this player the *attacker*.
- Player behavior is a decision, not a random event.
- We can be operator/defender or attacker, based on context.

Attacker – Defender (AD)

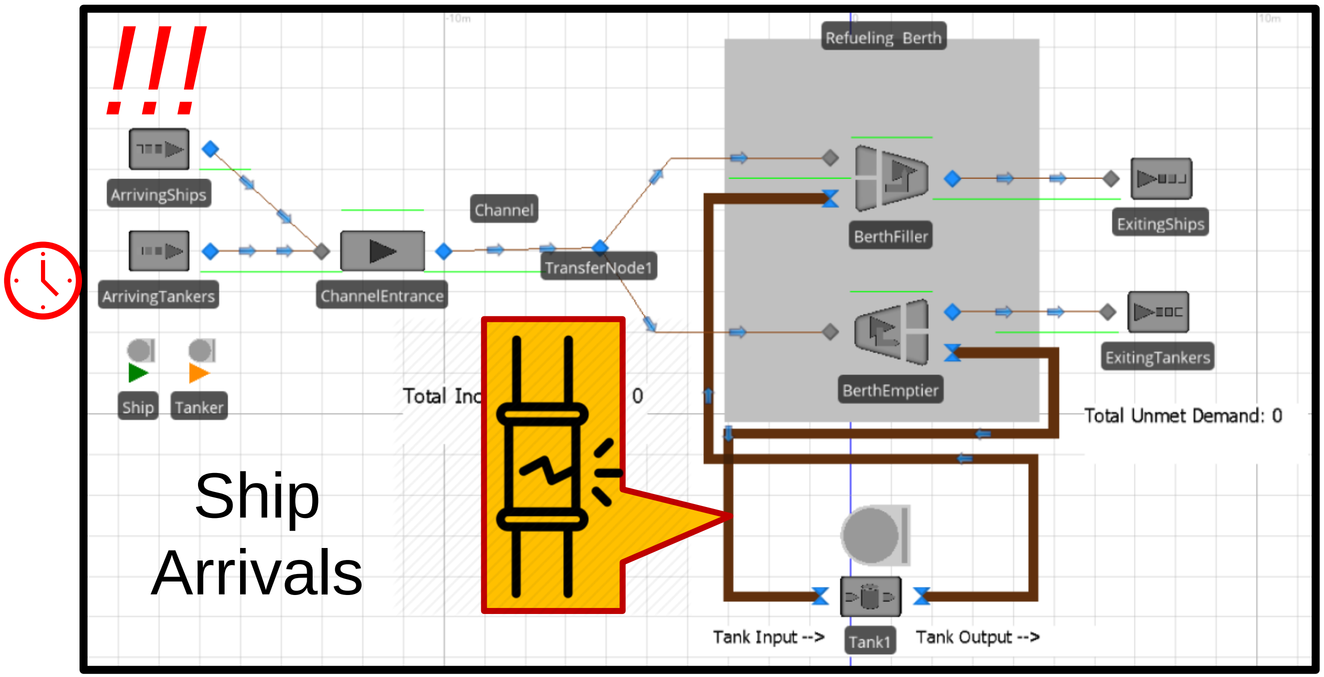
Defender – Attacker – Defender (DAD)

Investments in hardening, redundancy, etc., limited by budget.	Attacks limited by capability of the “attacker” and defenses	Optimal operation of the system, even after loss of components

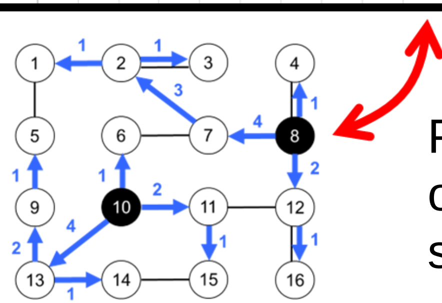
Alderson, D.L. et al. 2014. “Assessing and Improving Operational Resilience of Critical Infrastructures and Other Systems.” INFORMS, Hanover, MD, 180-215.

Resilience Framework (Pulliam)

Simio Queuing Model of Ship Arrival and Refueling

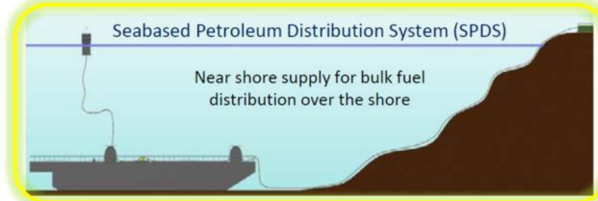


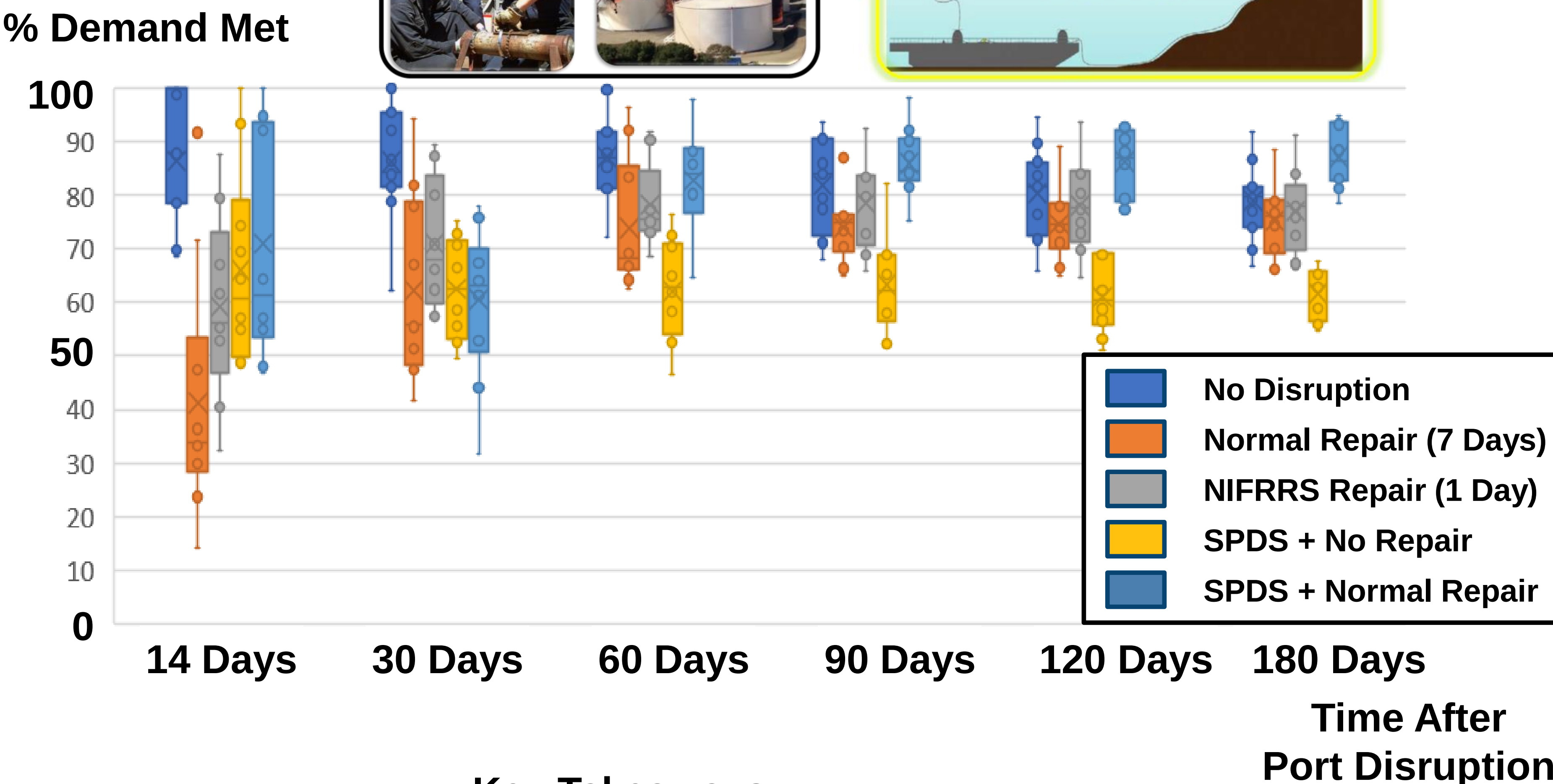
Fuel Piers Berths for Delivery and Resupply



Possible to connect to onshore fuel network serving an installation

Resilience Solutions (Pulliam)





Key Takeaways:

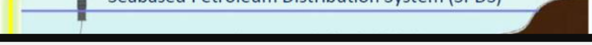
NFIRRS is the same or better than SPDS for Less than 1 Month

SPDS + Repair Reduces Cumulative Impacts and Improves Operations

Resilience Solutions (Pulliam)

Navy Fuels Infrastructure Rapid Repair Solutions (NFIRRS)

Seabased Petroleum Distribution System (SPDS)



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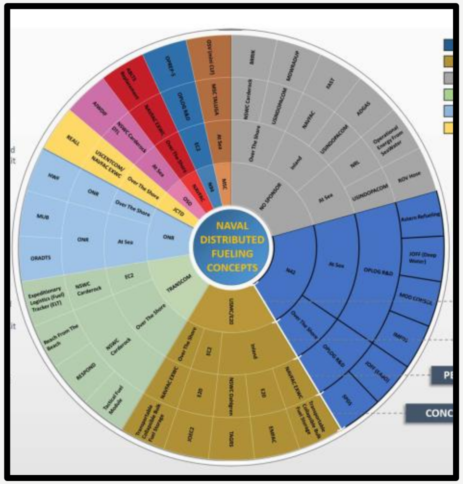
Results Presented to Naval Fuels Research Community
Thesis Won MORS Tisdale Award



"We plan to use LT Pulliam's framework and model to inform infrastructure posturing decisions, acquisition planning, and identifying vulnerabilities."

– Cody M. Reese, NAVFAC EXWC

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NFIRRS is the same or better than SPDS for Less than 1 Month
SPDS + Repair Reduces Cumulative Impacts and Improves Operations