Operational Resilience Analysis and Capacity Building in the US Virgin Islands

David L. Alderson, PhD

Associate Professor, Operations Research Department

Director, Center for Infrastructure Defense

Naval Postgraduate School

Workshop: Fundamentals of Microgrid Analysis and Design
Sandia National Laboratories & University of the Virgin Islands
St. Croix Campus (24 Oct 2018) & St. Thomas Campus (26 Oct 2018)

Naval Postgraduate School (NPS)

America's national security research university

History Highlights

1909 **Founded at U.S. Naval Academy**

1951 **Moved to Monterey, CA**

Operations Research Curriculum

- Facilities of a graduate research university
- Faculty who work for the U.S. Navy, with clearances
- Students with fresh operational experience

FY2017:

- 65 M.S. and 15 Ph.D. programs
- 612 faculty
- 1432 resident students includes (166 international / 47 countries)
- 909 distributed learning students

Operations Research at NPS

- Operations Research (OR) is the science of helping people and organizations make better decisions using
  - mathematical models, statistical analyses, simulations
  - analytical reasoning and common sense

  to the understanding and improvement of real-world operations.

- OR originated during World War II. The military uses OR at the strategic, operational, and tactical levels.

- Biggest users of OR: modern corporations
  - Supply chain logistics
  - Manufacturing and production planning
  - Scheduling

- NPS has the oldest OR instructional program in the U.S.

NPS Center for Infrastructure Defense (CID)
Operations Research Department

David Alderson
Associate Professor, OR
Director, NPS Center for Infrastructure Defense
Ph.D., Stanford University, 2003

Gerald Brown
Distinguished Emeritus Professor, OR
Member, National Academy of Engineering
Ph.D., U.C.L.A., 1974

W. Matthew Carlyle
Professor & Chair, OR

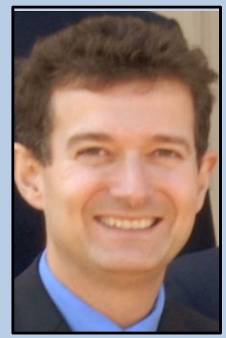
Ph.D., Stanford University, 1997

Robert Dell
Professor, OR

Ph.D., S.U.N.Y. Buffalo, 1990

Daniel Eisenberg
Research Assistant Professor, OR

Ph.D., Arizona State University, 2018



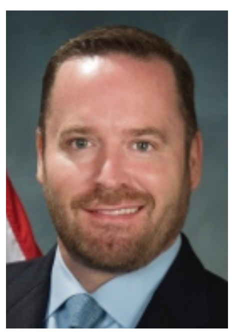
Javier Salmerón
Associate Professor, OR

Ph.D., Universidad Politécnica (Spain), 1998

NPS Energy Academic Group (EAG)

Dan Nussbaum
Visiting Professor, OR
Chair, NPS Energy Academic Group

Ph.D., Michigan State Univ., 1971



Alan Howard
Deputy Director, NPS Energy Academic Group

MBA/MIM in International Management, 2000

Jack Templeton
Program Manager, NPS Energy Academic Group

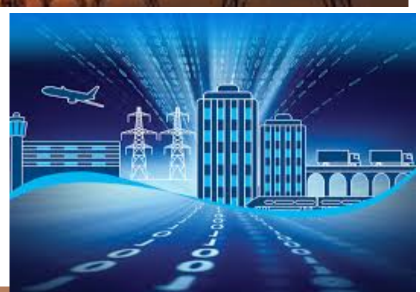
MSM Defense Systems Analysis, NPS, 2013

What is Critical Infrastructure?

- ***Critical Infrastructure (CI)***: "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" ***--Section 1016(e) of the USA PATRIOT Act of 2001***

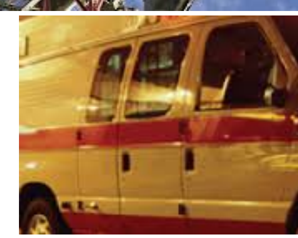












Critical Infrastructure Systems:
NPS has a unique perspective and capability

- We have been studying critical infrastructure for decades.
- We look at our own domestic infrastructure through the eyes of intelligent adversaries.
- We have conducted over 150 “red team analyses” to plan attacks on our own infrastructure (and determine how to mount effective hardening and defensive efforts)

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Goals For This Session

- **10 key ideas** for how to assess and improve operational resilience of critical infrastructures
- Ongoing work in applying these ideas to the USVI

Idea #1: **Start by focusing on delivery of services**,
<u>not</u> mitigation of hazards/threats

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What we need to do
(operation)

- Electricity
- Fuels
- Transportation
- Communications
- Water & Wastewater
- Emergency response

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What we need to do (operation)	**What can go wrong** (interdiction)

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What can go wrong
(interdiction)

- Extreme Weather
  - Coastal Flooding
  - Rainfall Flooding
  - Wind
  - Drought
- Human accident
- Technological failure
- Deliberate attack

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Idea #2: **Avoid getting stuck on predefined threat scenarios.**

- Surprise Happens. Things we have not imagined.
- Tunnel vision (on the last disaster). Need to be proactive, not reactive.

A policy shift toward "operational resilience"

U.S. National Strategy for Homeland Security (2007)

"We will not be able to deter all terrorist threats, and it is impossible to deter or prevent natural catastrophes. We can, however, mitigate the Nation's vulnerability to acts of terrorism, other man-made threats, and natural disasters by **ensuring the structural and operational resilience** of our critical infrastructure and key resources" (p. 27)

"We must now focus on the **resilience of the system as a whole** – an approach that centers on investments that make the system better able to absorb the impact of an event without losing the capacity to function" (p.28)

Most recently: U.S. Presidential Policy Directive (PPD)-21: Critical Infrastructure Security and Resilience, 2013.

“system as a whole” and “capacity to function”

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How to Think About Critical Infrastructure (CI)

- A list of *assets*
- An interconnected (network) *system* that works to achieve a particular function

“system as a whole” and “capacity to function”

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Idea #3: We need to think in terms of **systems**.

We want to make our operations (public and private) resilient to disruptive events.

We need our infrastructure systems to continue to function even when “bad things” happen.

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A shift toward "operational resilience"

- DOD Directive 3020.40: Mission Assurance (2016)

  DOD has recently reorganized its efforts to protect defense-related critical infrastructure under a broader program of *mission assurance*

- Key recognition
  - *Assets* work together as *systems* to provide *function*
  - Function enables *capability*
  - Capability supports *mission*
- Focus needs to remain on the relationship between the infrastructure asset and the missions it supports

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Idea #4: **Resilience is not about what you <u>have</u>, its about what you <u>do</u>!** This is a common misperception. (Think of <u>*safety*</u> as another concept with this feature…)

Idea #5: Take an ”operational” perspective

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Need to understand the demands of the population

- Demographics
- Geography
- Population density
- Special needs

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Move goods/services from areas of supply to demands:
- Must include infrastructure owners and operators
- Both public <u>and</u> private!

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Idea #6: Often represented as **flows** through **networks**.

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Idea #7: Measure **performance.** Define **mission success.**

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BUT… Systems Are Complicated, Sometimes Complex

- Interactions often non-additive and non-intuitive.
- An event in one location can often affect things that are far away, and it can be hard to predict how this happens.
- The contribution/importance of a single component to system function may depend on interactions with other components.

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- When determining how best to protect systems, a natural question is, *"What components are most critical?"*
- Better yet: *Which components, if lost, would be most disruptive to system function?*

Definition: A component is *critical* if losing it would significantly reduce system function (relative to the reduction from losing other components).

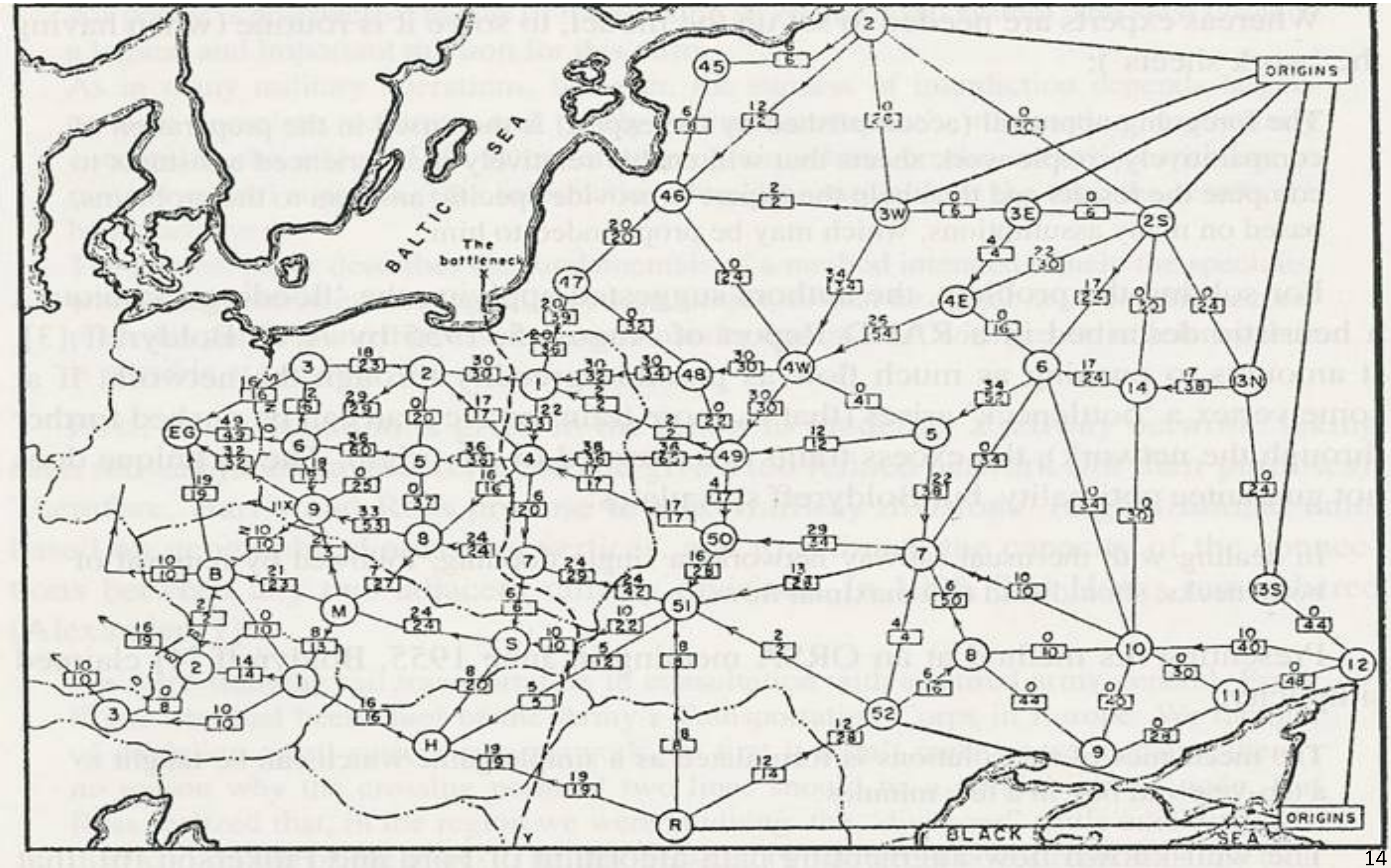
Let's use a historical example to illustrate…

The Russian Rail Network (circa 1955)

Data from Figure 7 of:

Harris, T.E., and Ross, F.S. (1955), *Fundamentals of a Method for Evaluating Rail Net Capacities* (SECRET, declassified 1999), RM-1573, RAND Corp.

What is the capacity of the USSR to deliver materiel to Europe via rail?



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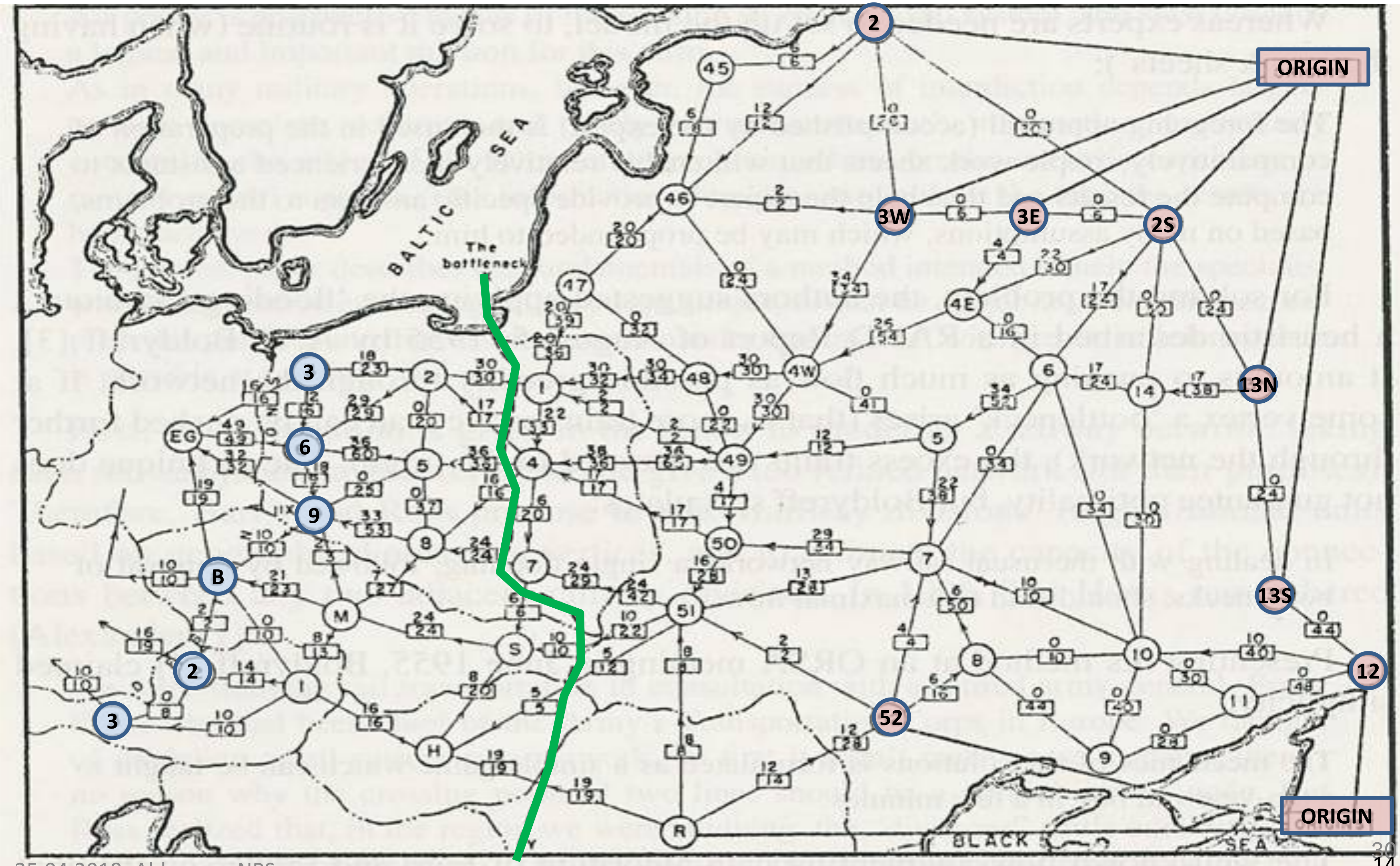
destination nodes

minimum capacity cut

origin nodes



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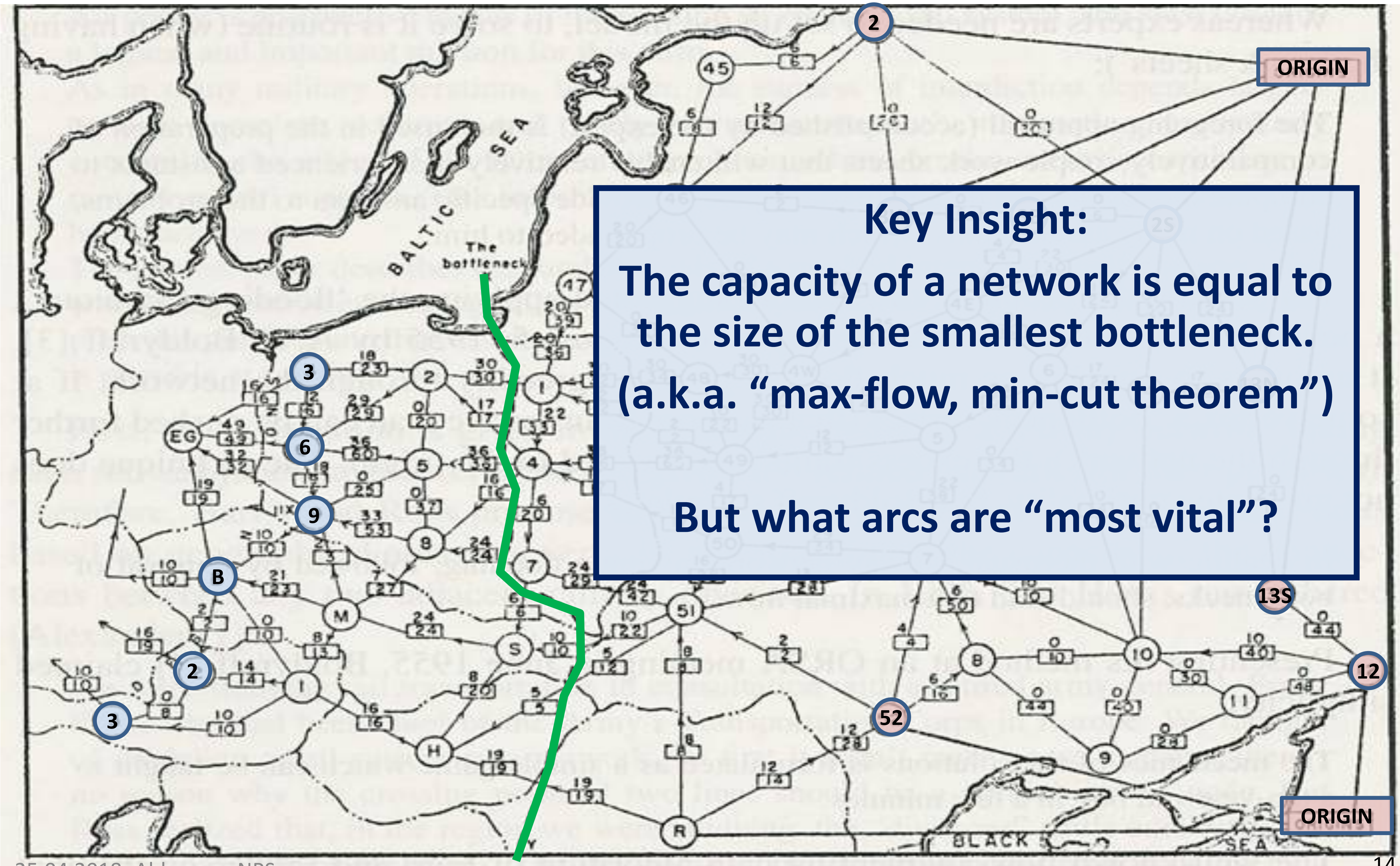

Key Insight:

The capacity of a network is equal to the size of the smallest bottleneck.

(a.k.a. "max-flow, min-cut theorem")

But what arcs are "most vital"?

Finding the “Most Vital” Arc(s) is not trivial!

- It requires you to consider not only the current paths through the network but also any alternate paths
- Because… the system can adjust its flows in response to a disruption!

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Possible "guessing rules" for determining what is most vital
(Ahuja, Magnanti, and Orlin, "Network Flows", Prentice-Hall, 1993)

- An arc having the *largest capacity*
- An arc carrying the *largest flow in the optimal solution*
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- *Any most-vital arc is in some minimum-capacity cut*

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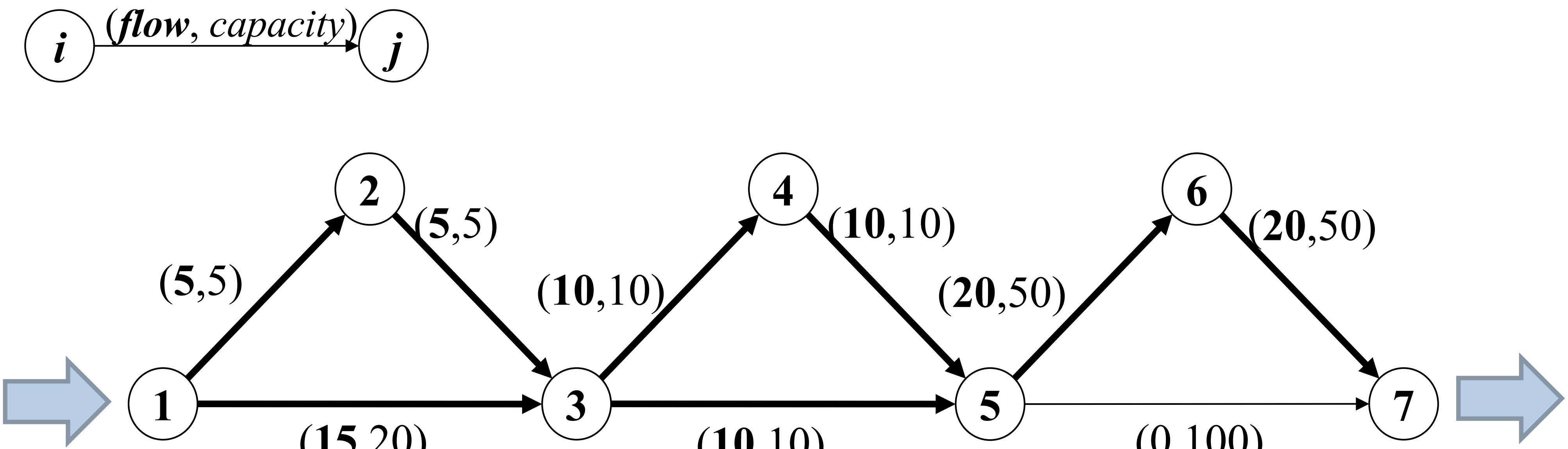
In general, none of these "guessing rules" work!

counter-example: guessing to find most vital arc



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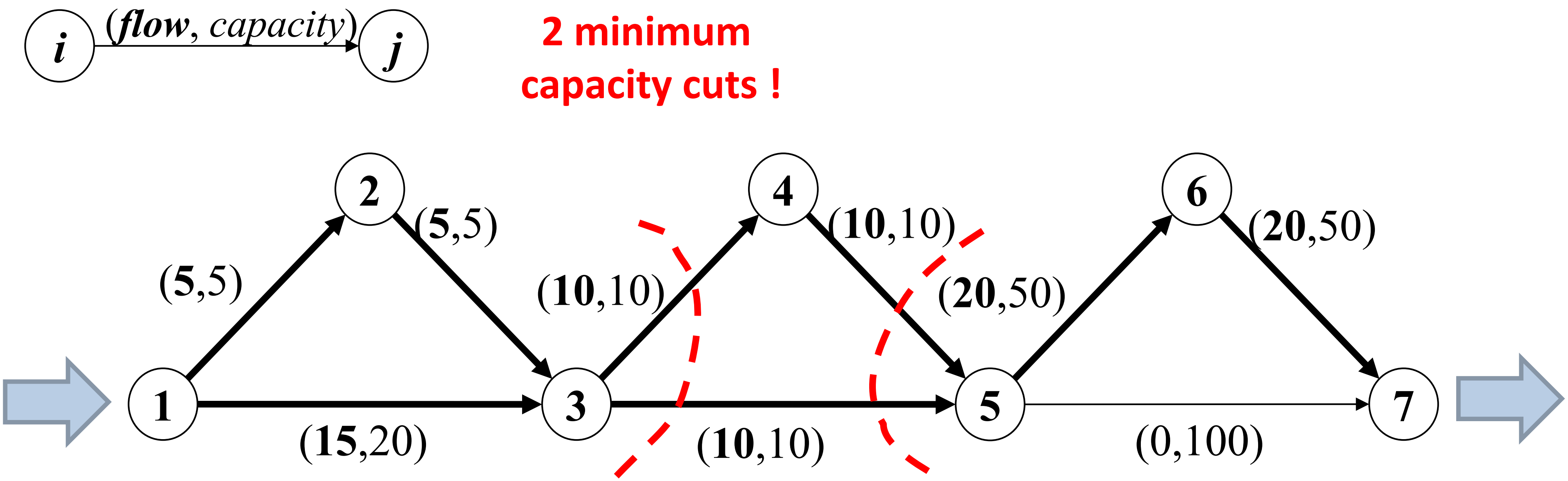

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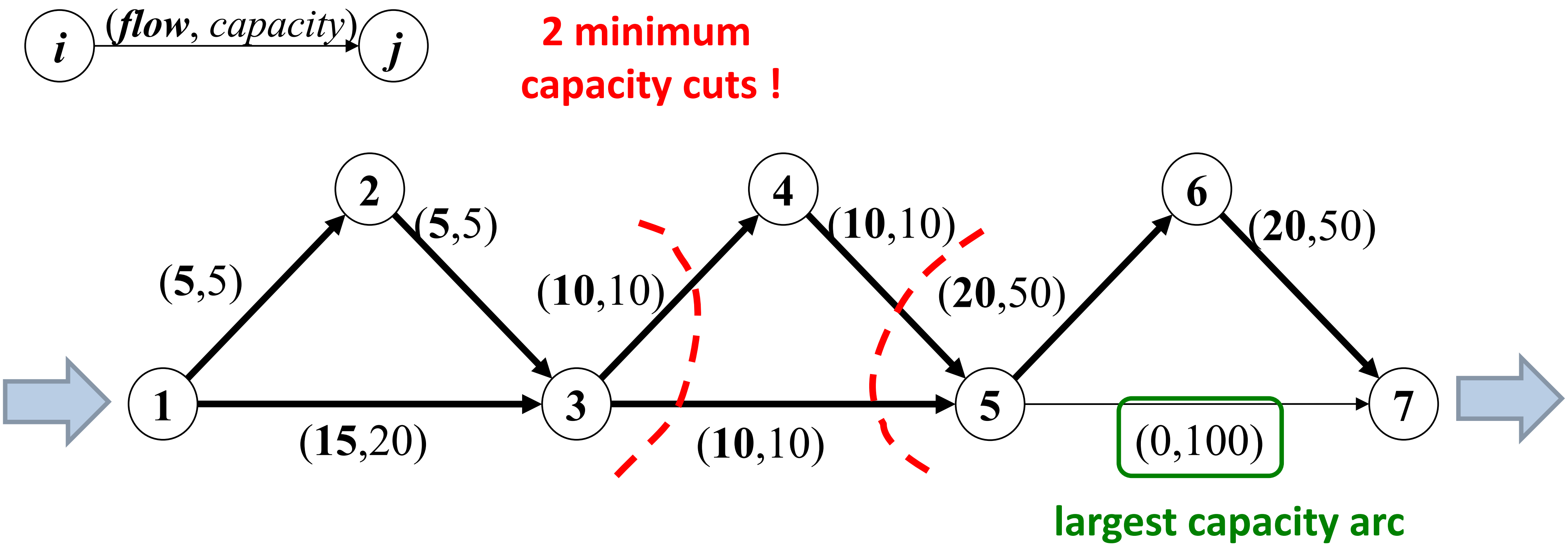

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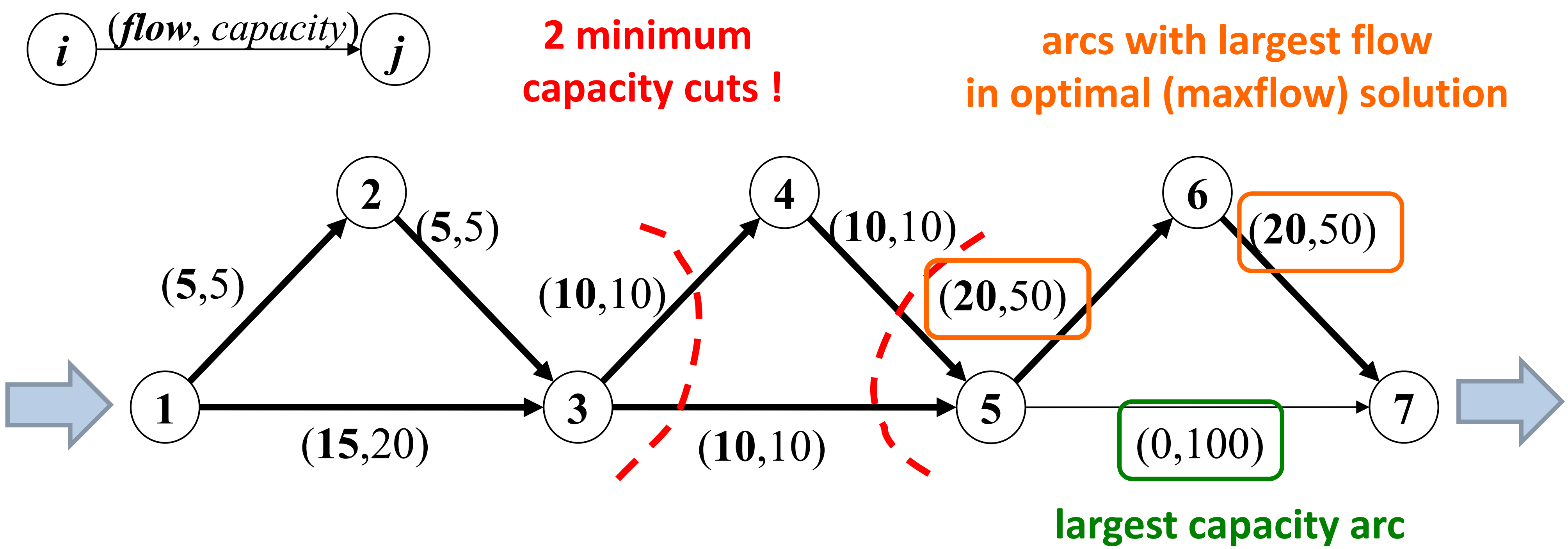

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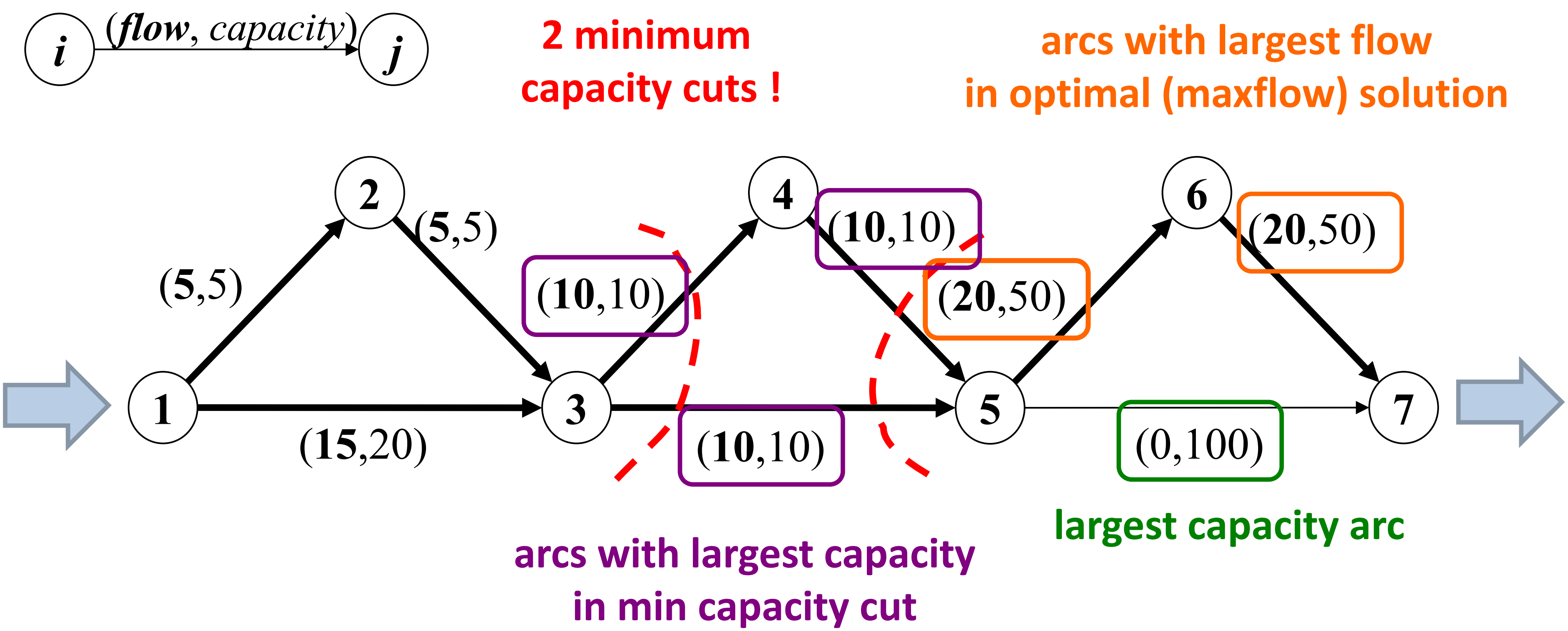

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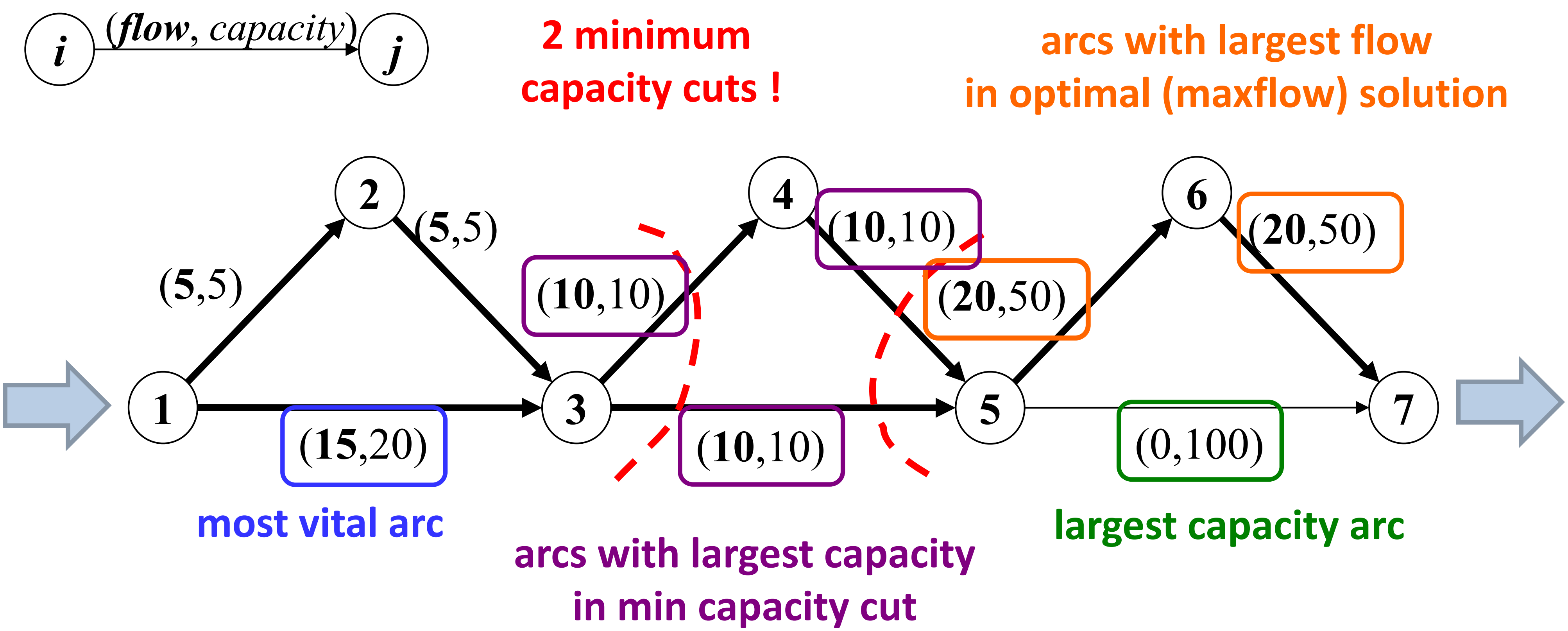

In general, you cannot reliably guess. Instead, determining a most vital arc requires solving a *network interdiction problem*.

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Our Approach in a Nutshell

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We call these Attacker-Defender and Defender-Attacker-Defender models.

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- It helps to focuses on system operation.
- It helps to discover vulnerabilities.
- It helps to uncover interdependencies.
- It helps to think about mitigation.

Our experience: Large-scale, long-term interruptions in critical infrastructure services can be caused by things much smaller than two Category-5 hurricanes!

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Idea #10: **Investing for resilience can work better** when you to think about the system as a whole.

- Hardening (reinforcement)
- Redundancy (backups, spares)
- Capacity expansion
- New infrastructure

This means studying more than just "how we actually do it now".

It requires we also consider "how could we do it now (and in the future)"!

We have used scores of these models to assess resilience for a wide range of systems

Operator Models

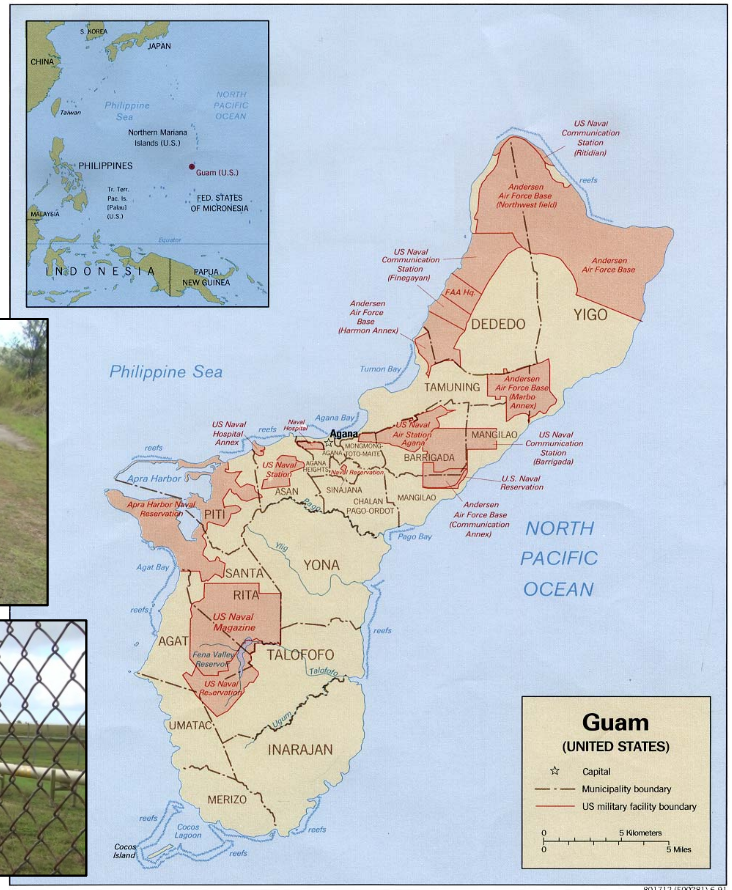
- Shortest-path problems
- Max-flow problems
- Min-cost network flow problems
- Multi-commodity flow problems
- Project scheduling problems
- Linear programs
- Integer-Linear programs
- Nonlinear programs
- Nonlinear-Integer programs

Applications

- Electric power
- Potable water
- Fuel pipelines
- Roadway transportation
- Multi-modal shipping
- Ports
- Supply chains
- Telecommunications
  - Undersea cables
  - Wireless network design
- Interdependent infrastructures

These techniques scale up to realistic size and fidelity, and admit a host of standard models, many already in use by system operators.

Case Study: Guam Power Authority



Guam Power Authority's transmission system (115-13.8 kV):

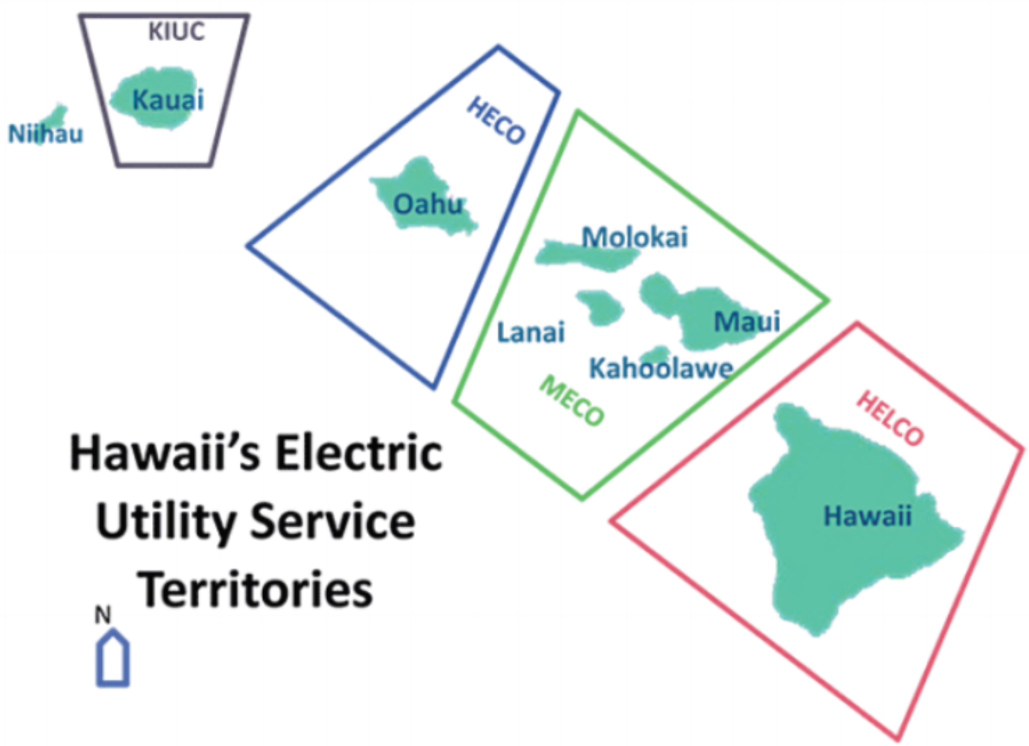
- ~100 buses
- ~50 HV lines
- ~50 transformers
- 10s of substations
- 10s of generating units:
  - >550 MW

Both Attacker and Defender Analysis

Reference: Salmerón, J., Alderson, D., Brown, G., and Wood, R.K., 2012, **Resilience Report: The Guam Power Authority Electric Power Grid: Analyzing Vulnerability to Physical Attack (U)**, Center for Infrastructure Defense Technical Report NPS-OR-12-002, May. *Distribution authorized to DoD and DoD Contractors only due to infrastructure vulnerability analysis (10 May 2012). Other requests for this document must be referred to President, Code 261, Naval Postgraduate School, Monterey, CA 93943-5000 via the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Ft. Belvoir, VA 22060-6218.*

Prepared for: Air Force Research Lab (AFRL), Airbase Technologies Division, 139 Barnes Drive, Suite 2, Tyndal Air Force Base, FL 32403-5323.

Case Study: Hawaii



Map credit: "Hawai'i Energy Facts and Figures: May 2015," Hawai'i State Energy Office

- 10s buses
- ~100 high-voltage AC transmission lines
- no DC lines
- ~100 transformers
- 10s generating units: total gen. capacity of ~2,500 MW
- Total load: ~1,200 MW

Attacker, Defender, & Spare Parts Analysis

- Can a small number of coordinated attacks inflict significant damage for which repair would require considerable reconstitution time? What is the best means of hardening against such attacks?
- How can a limited stockpile of medium- and high-voltage spare transformers contribute most to mitigating vulnerability, i.e., to "increasing system resilience."

Reference: Salmerón, J., Alderson, D., and Brown, G., 2018, **Resilience Report: Analysis of Hawaiian Electric Power Grid to Physical Attack (U)**, NPS Technical Report NPS-OR-18-001R, February. Restricted distribution (PCII).

Prepared for: Department of Homeland Security, Infrastructure Protection Division.

Critical Infrastructure Systems: NPS has a unique perspective and capability

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Goals For This Session

- 10 key ideas for how to assess and improve operational resilience of critical infrastructures
- **Ongoing work in applying these ideas to the USVI**

Our research is part of a broader team effort

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

FEMA

NREL National Renewable Energy Laboratory

UNIVERSITY OF THE VIRGIN ISLANDS · 1962 ·

NPS PRAESTANTIA PER SCIENTIAM 1909

Our work in the USVI: several related research efforts

Effort 1 - Modeling and analysis of interdependent critical infrastructure systems

- Energy (emphasis on electric power)
- Water (emphasis on potable storage and distribution)
- Transportation
- Telecommunications

Effort 2 - Support for development of a new Hazard Mitigation and Resilience Plan

- in partnership with UVI / VITEMA

Effort 3 - Capacity building & workforce development program

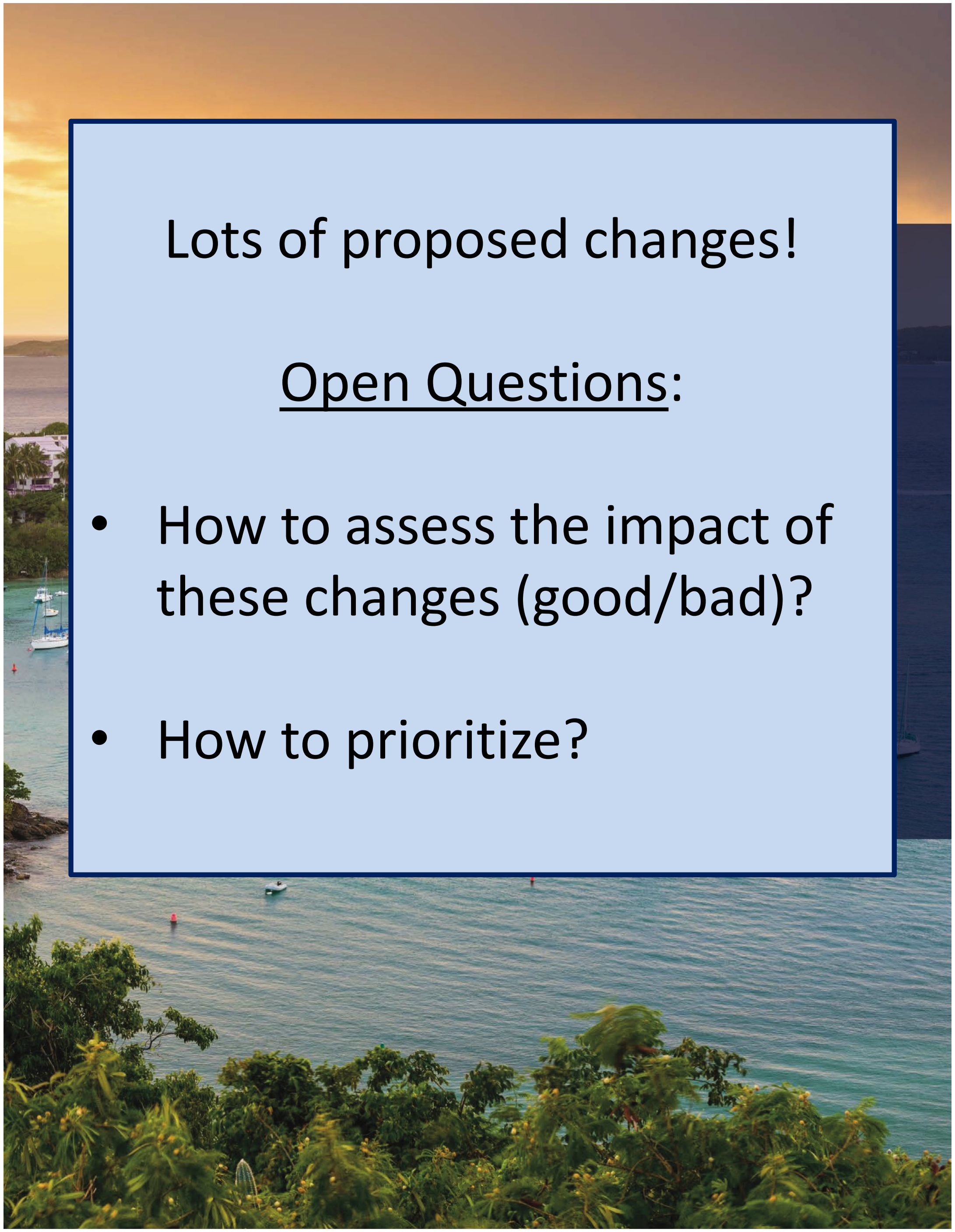
- in partnership with UVI

Our work in the USVI: several related research efforts

27 Feb 2018	Project Start (funds available)
21 Mar	remote participation in USVI Energy Roundtable
26-30 Mar	1st NPS site visit to STX, STT
11-15 Jun	2nd NPS site visit to STX, STT
14-15 Jun	UVI/VITEMA Hazard Mitigation Workshop
21 Sep	MS Thesis by LCDR Brendan Bunn
20 Oct	Technical report (final draft)
22-26 Oct	3rd NPS site visit to STX, STJ, STT

- Bunn BB, 2018, **“An Operational Model of Interdependent Water and Power Distribution Infrastructure Systems,”** M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA, September 2018.
- Alderson DL, Bunn BB, Eisenberg DA, Howard AH, Nussbaum DE, Templeton JC, **“Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment,”** NPS Technical Report, Naval Postgraduate School, Monterey, CA, October 2018 (forthcoming).

https://www.usvihurricanetaskforce.org/



Lots of proposed changes!

Open Questions:

- How to assess the impact of these changes (good/bad)?
- How to prioritize?

228 proposed initiatives across a variety of sectors:

- Climate Analysis (5)
- Energy (17)
- Private Sector Comms (14)
- Public Sector Comms (11)
- Transportation (24)
- Water (11)
- SolidWaste and Wastewater (26)
- Housing and Buildings (11)
- Health (21)
- Vulnerable Populations (12)
- Education (20)
- Economy (9)
- Non-profit, Philanthropy, and Voluntary Organizations (6)
- Government Response (41)

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Alderson DL, Bunn BB, Eisenberg DA, Howard AH, Nussbaum DE, Templeton JC, **“Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment,”** NPS Technical Report, Naval Postgraduate School, Monterey, CA, October 2018 (forthcoming).

Key Concept: The Need for an Operational View of Resilience

Report Contributions:

1. Explaining the structure, function, and tensions associated with critical infrastructure that were chronic problems prior to the hurricanes.
2. Documenting hurricane response, recovery, and mitigation activities for these infrastructure systems after the hurricanes.
3. Discussing these changes in the context of potential barriers to resilience.

We face several barriers to resilience

Barrier 1: We don’t fully understand how vulnerable we are.

- owners, operators, or communities who manage infrastructure often do not have complete knowledge about their vulnerabilities

Barrier 2: We don’t know how best to create resilience.

- Tradeoffs/tensions between different mechanisms to achieve resilience
- Prioritization is difficult

Barrier 3: We don’t have incentives to create resilience.

- Hard to invest in mitigating something that has never happened
- Moral hazard: disincentives for investment

Barrier 4: We don’t know how to govern for resilience.

- Rules/regulations work against implementation of desired changes
- mismatch between infrastructure governance and infrastructure operation

Reference: Alderson DL, Bunn BB, Eisenberg DA, Howard AH, Nussbaum DE, Templeton JC, **“Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment,”** NPS Technical Report, Naval Postgraduate School, Monterey, CA, October 2018 (forthcoming).

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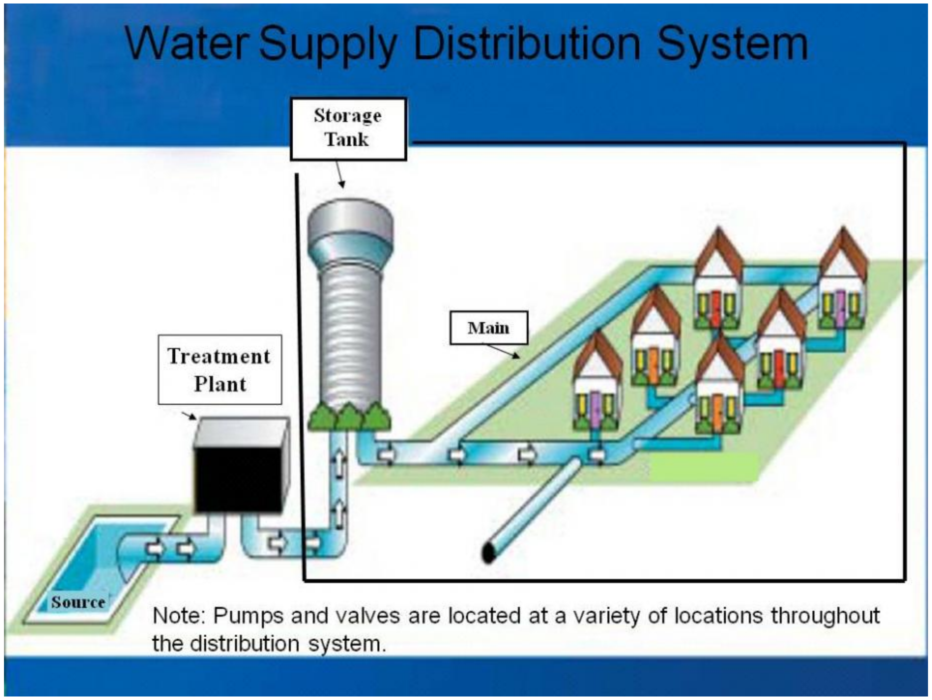
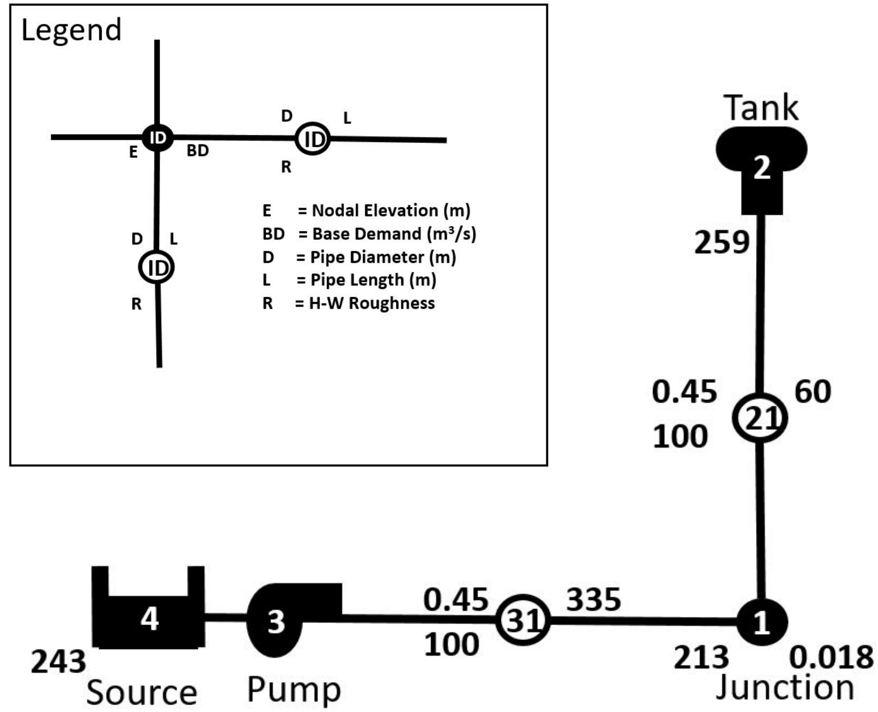
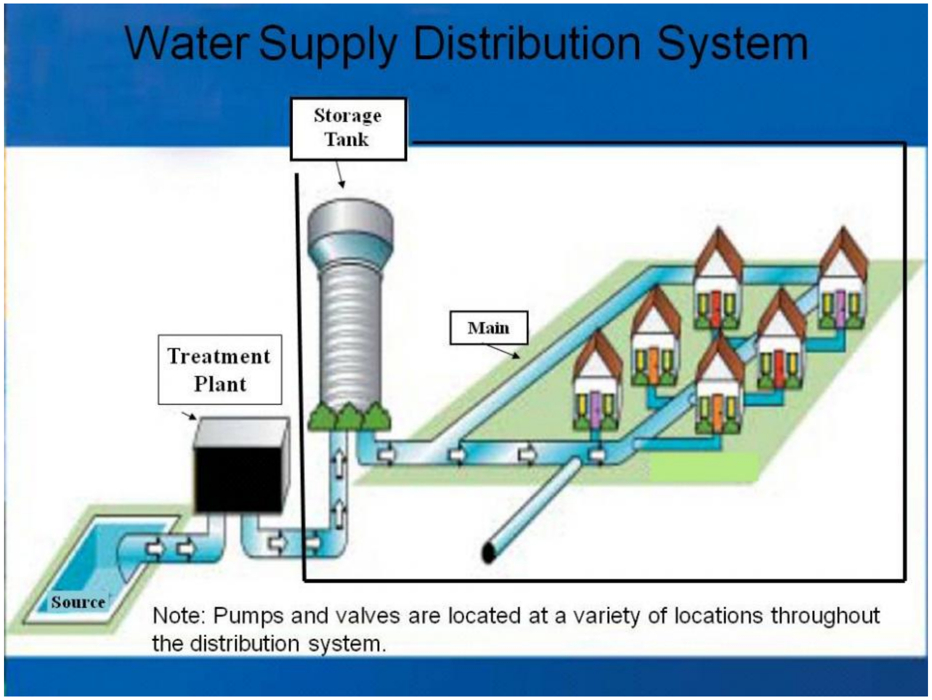
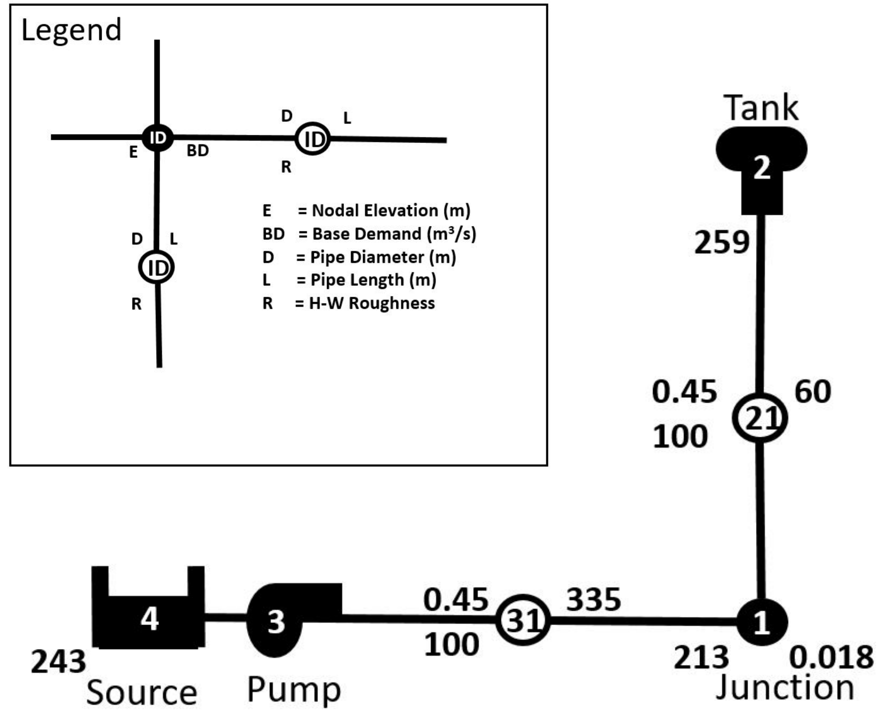

Water Supply Distribution System
Storage Tank
Main
Treatment Plant
Source
Note: Pumps and valves are located at a variety of locations throughout the distribution system.


Legend
ID
E
BD
D
L
R
E = Nodal Elevation (m)
BD = Base Demand (m³/s)
D = Pipe Diameter (m)
L = Pipe Length (m)
R = H-W Roughness
Tank
2
259
0.45
60
21
100
4
3
0.45
31
335
1
243
100
213
0.018
Source
Pump
Junction


Water Supply Distribution System
Storage Tank
Main
Treatment Plant
Source
Note: Pumps and valves are located at a variety of locations throughout the distribution system.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100
243
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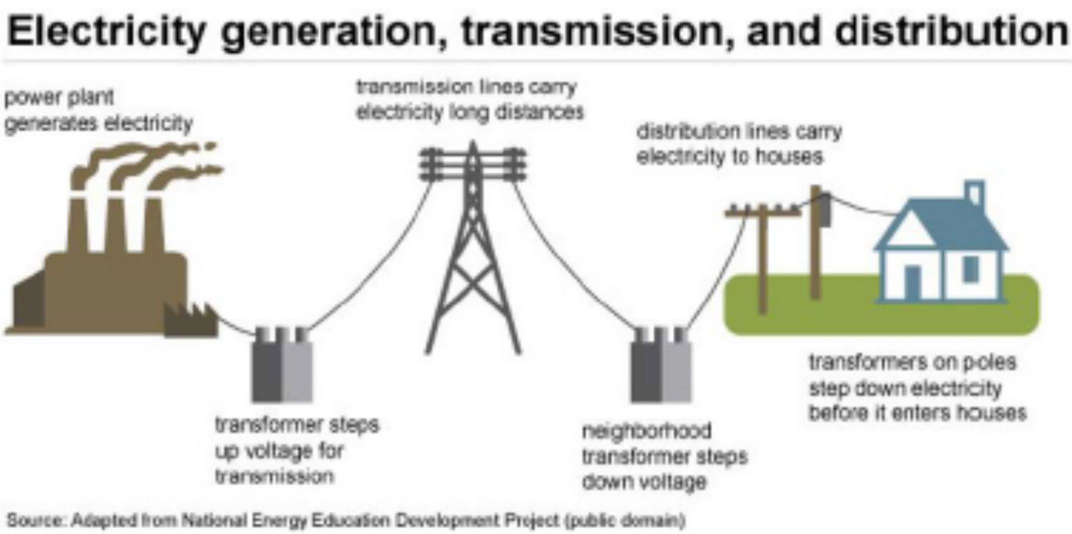
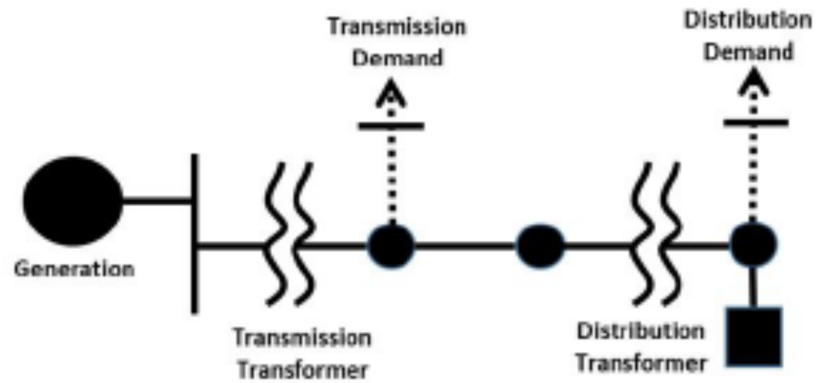
0.018
Source
Pump
Junction

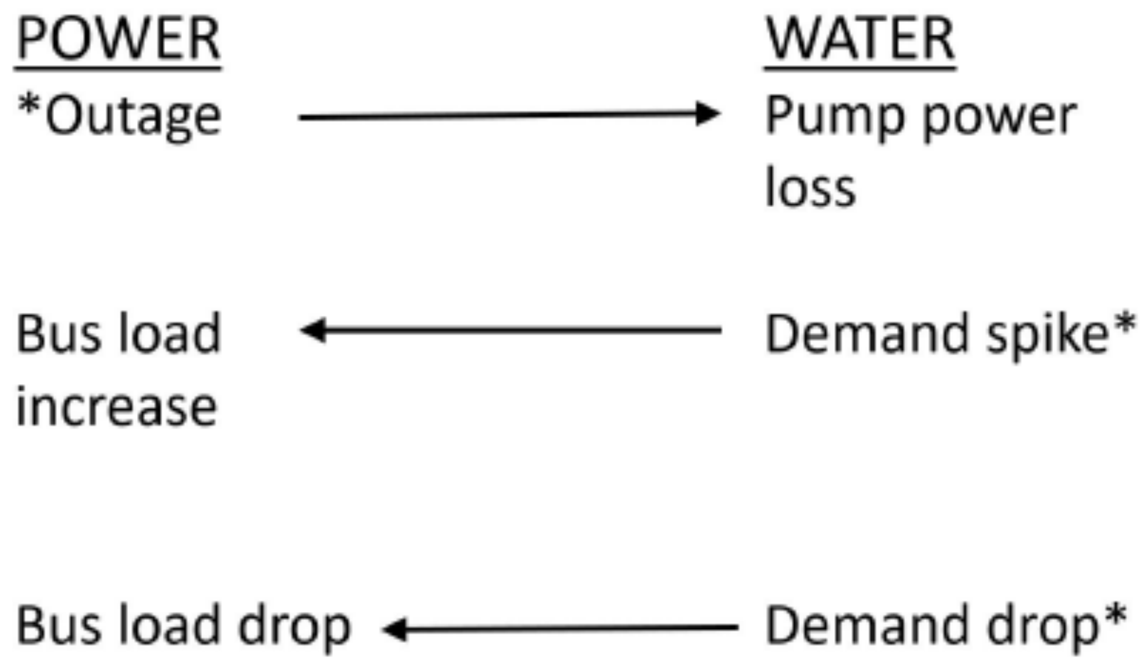

Electricity generation, transmission, and distribution
power plant generates electricity
transmission lines carry electricity long distances
distribution lines carry electricity to houses
transformer steps up voltage for transmission
neighborhood transformer steps down voltage
transformers on poles step down electricity before it enters houses
Source: Adapted from National Energy Education Development Project (public domain)

(a)

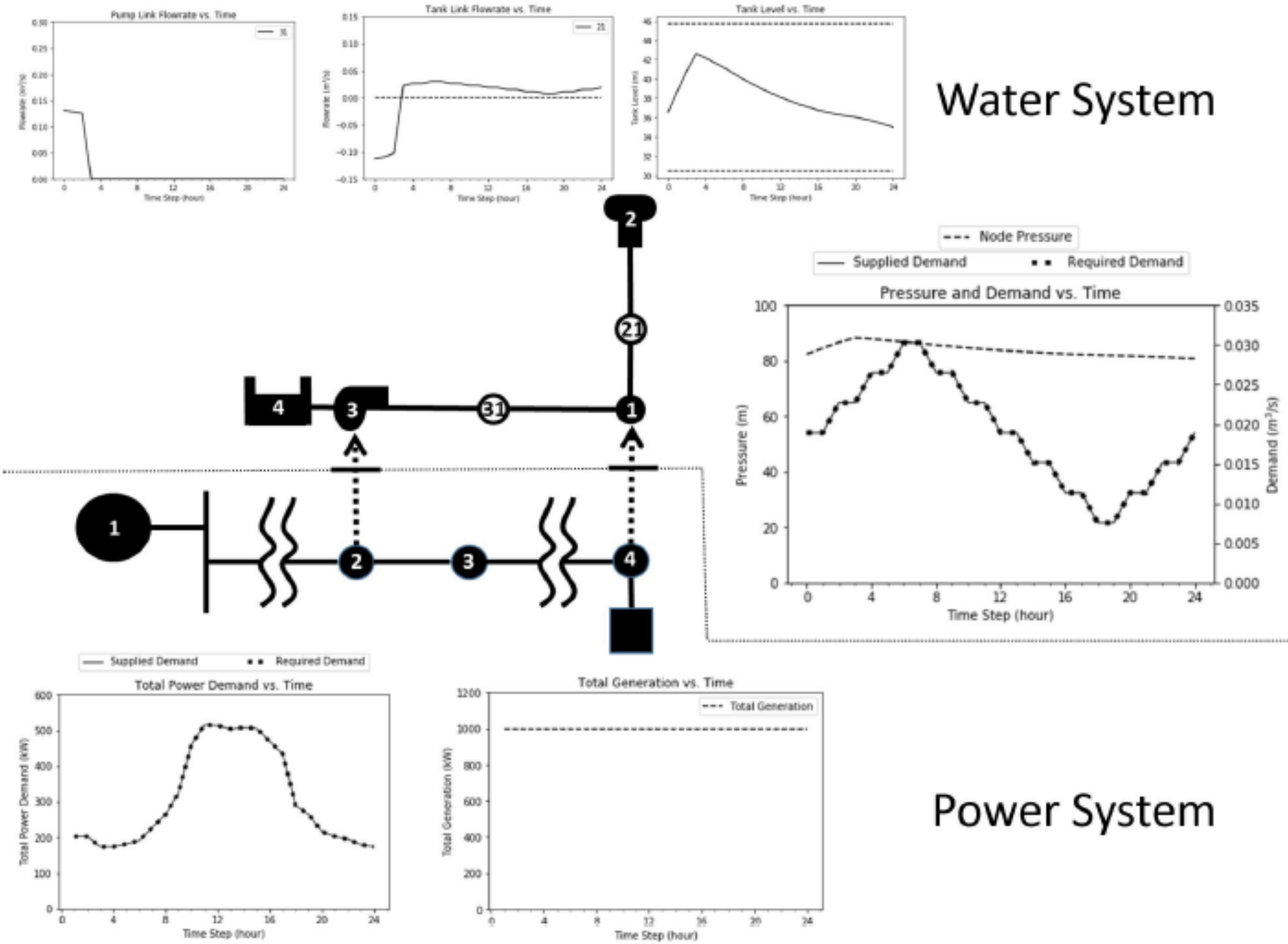

Transmission Demand
Distribution Demand
Generation
Transmission Transformer
Distribution Transformer

(b)

Power – Water Interdependencies

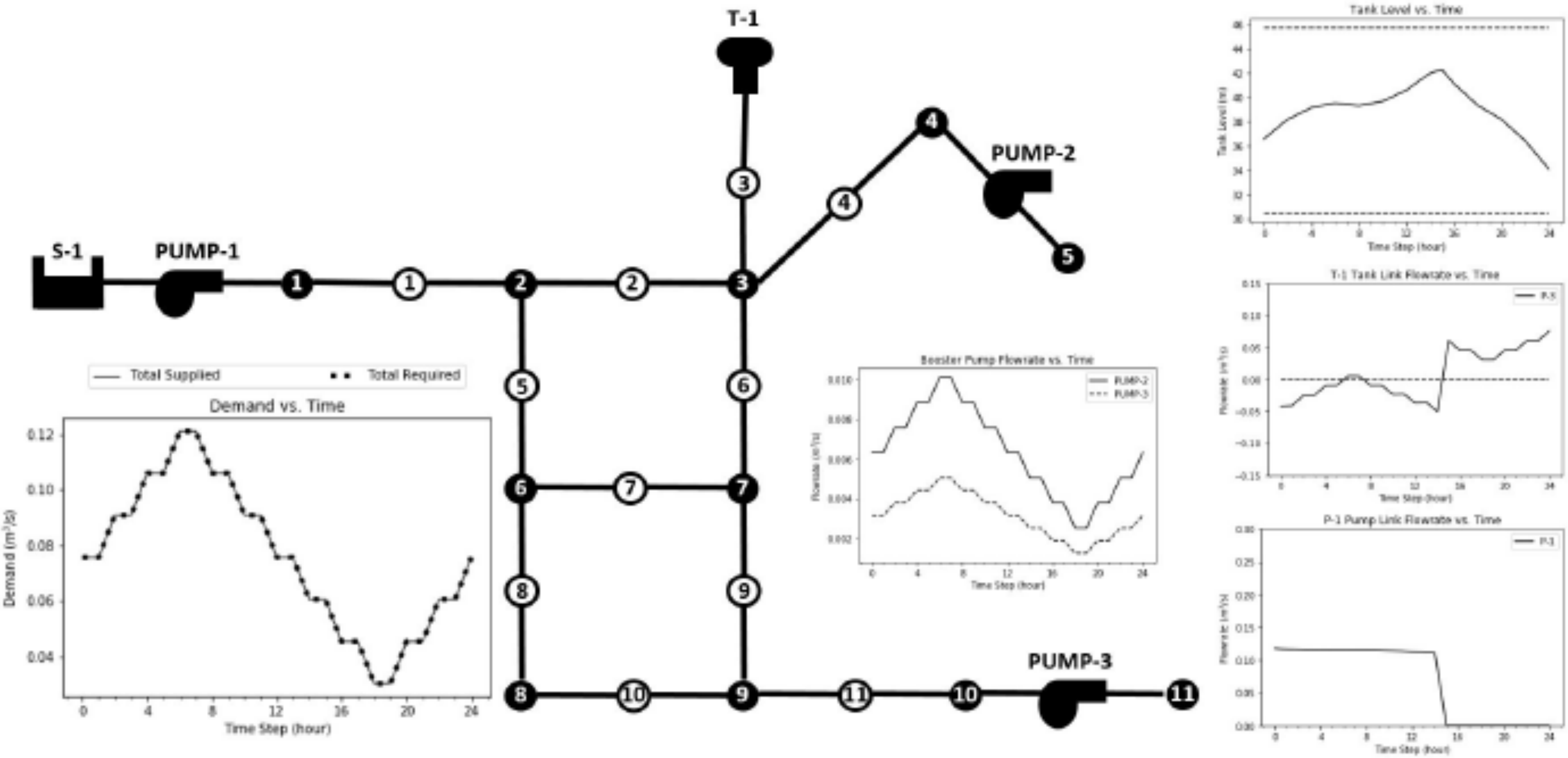


Excursions are denoted by originating failure events (asterisk) and their consequences across system boundaries.

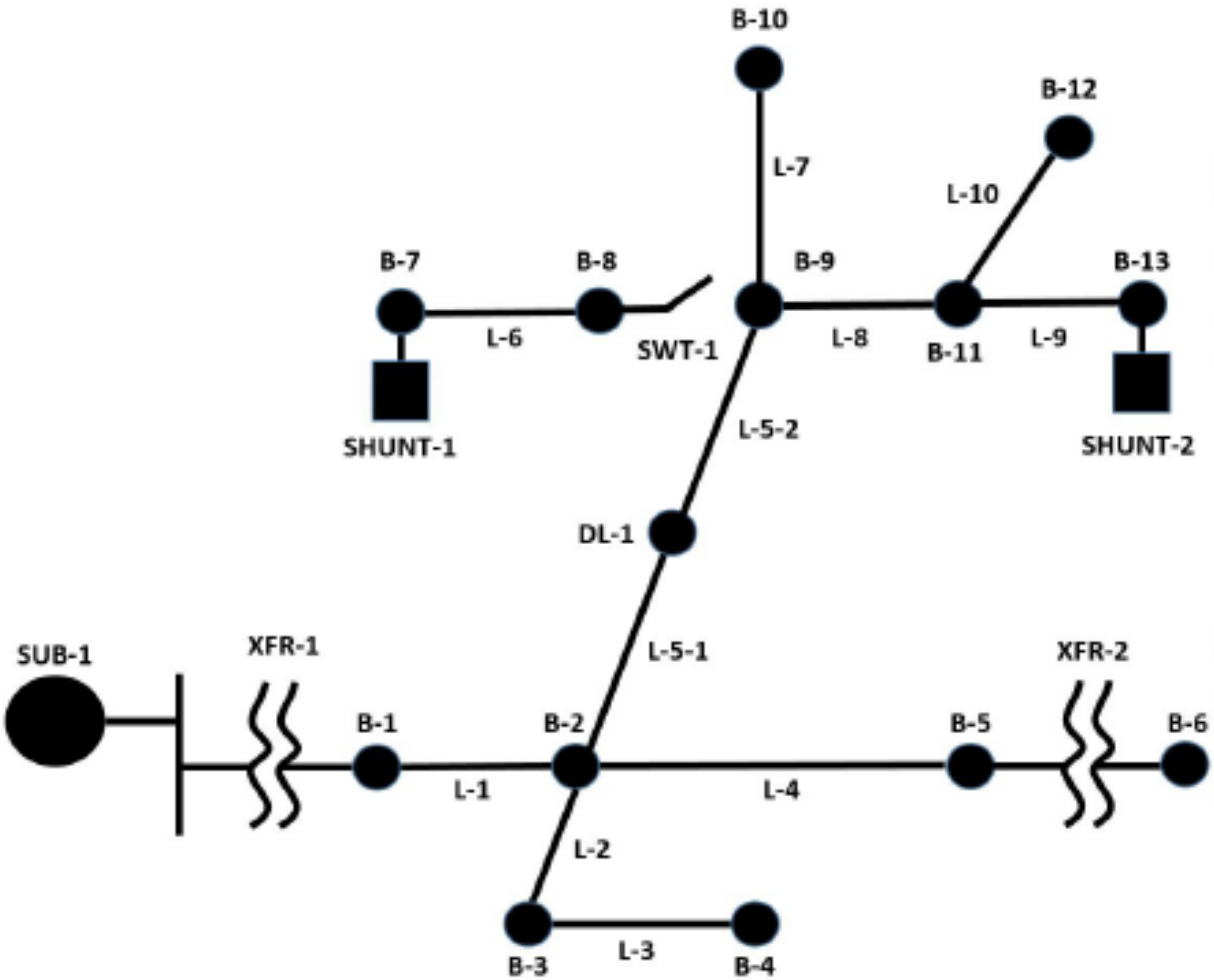


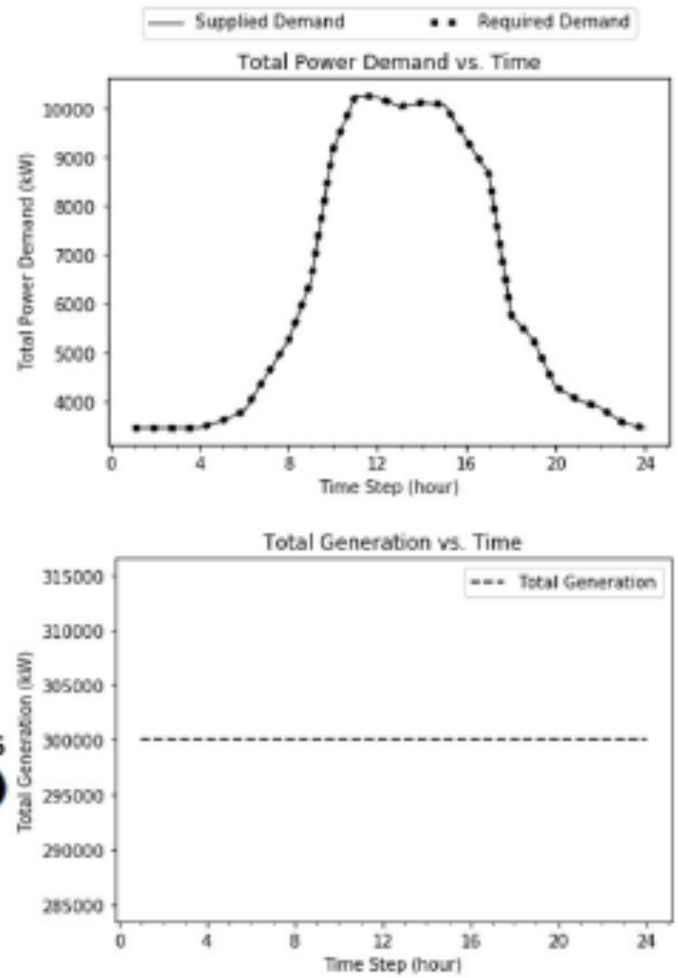
Pump Link Flowrate vs. Time
Tank Link Flowrate vs. Time
Tank Level vs. Time
Water System
Node Pressure
Supplied Demand
Required Demand
Pressure and Demand vs. Time
Pressure (m)
Demand (m^3/s)
Time Step (hour)
Supplied Demand
Required Demand
Total Power Demand vs. Time
Total Power Demand (kW)
Time Step (hour)
Total Generation vs. Time
Total Generation
Total Generation (kW)
Time Step (hour)
Power System

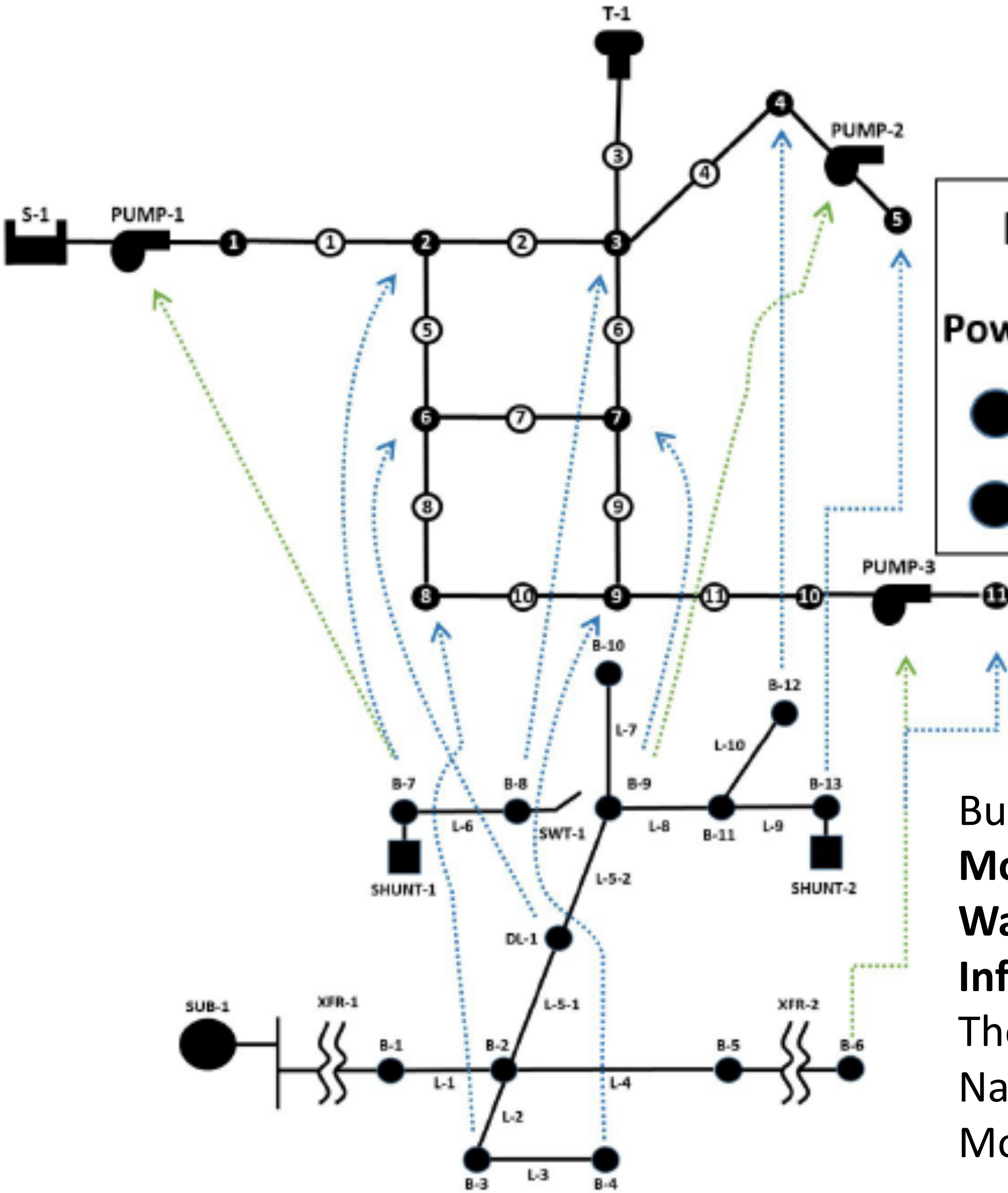
a more realistic (USVI) water distribution system

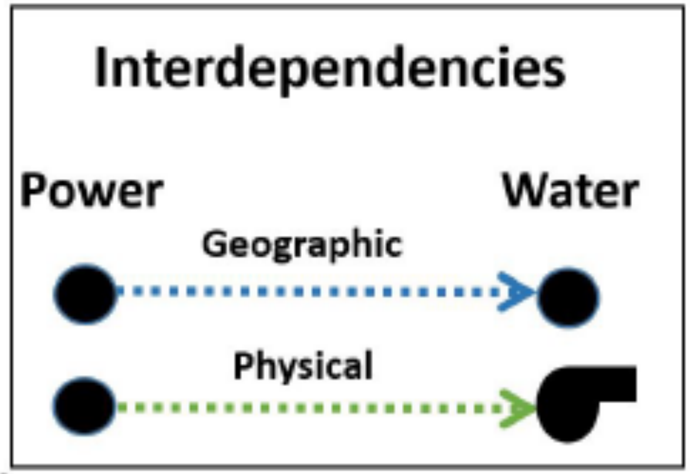


IEEE 13-bus electricity distribution network



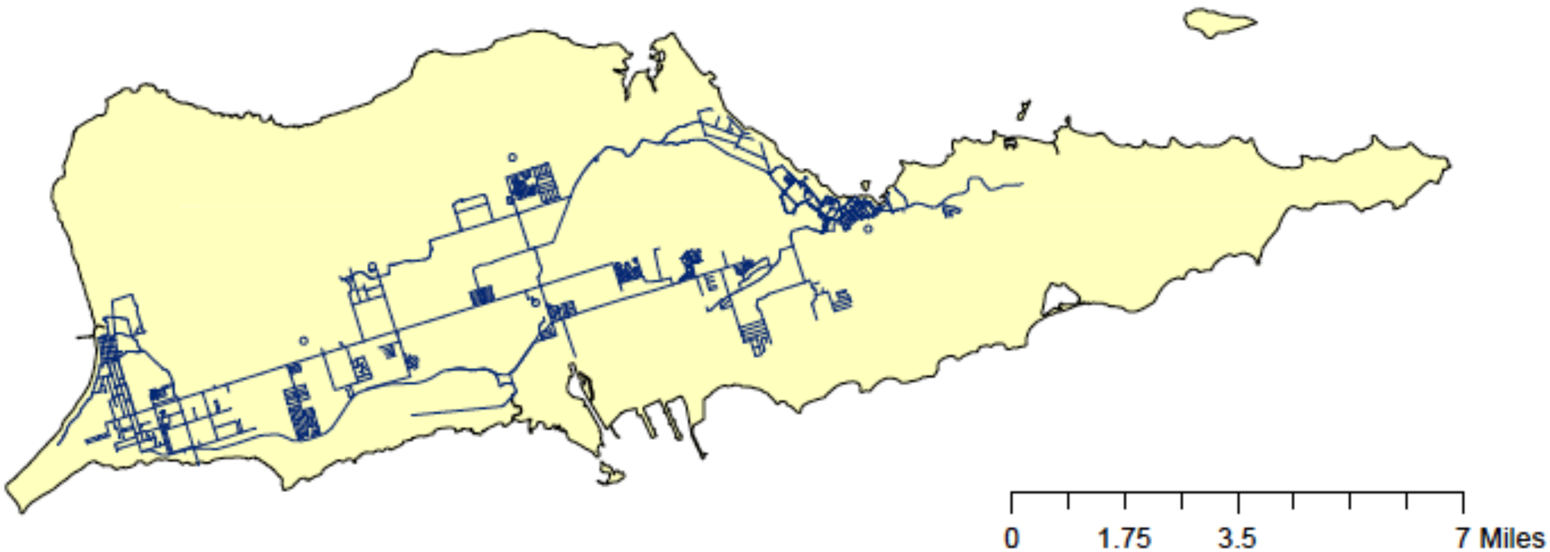




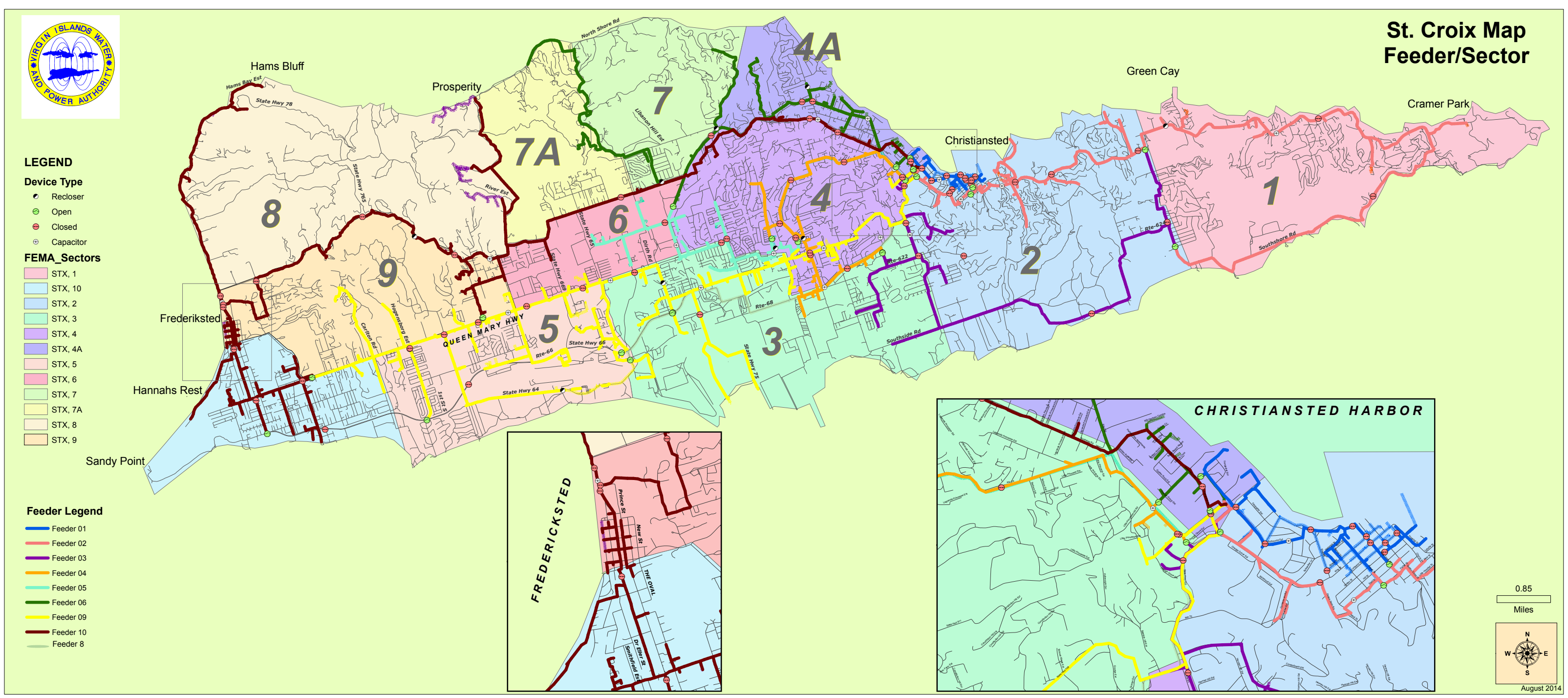


Bunn BB, 2018, **“An Operational Model of Interdependent Water and Power Distribution Infrastructure Systems,”** M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA, September 2018.

Ongoing work: St. Croix electric + water



St. Croix



Our work in the USVI: several related research efforts

Effort 1 - Modeling and analysis of interdependent critical infrastructure systems

- Energy (emphasis on electric power)
- Water (emphasis on potable storage and distribution)
- Transportation
- Telecommunications

Effort 2 - Support for development of a new Hazard Mitigation and Resilience Plan

- in partnership with UVI / VITEMA

Effort 3 - Capacity building & workforce development program

- in partnership with UVI

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- NPS Center for Infrastructure Defense

http://www.nps.edu/cid

References and Acknowledgments

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- Alderson, D.L., G.G. Brown, W.M. Carlyle. 2014. **"Assessing and Improving Operational Resilience of Critical Infrastructures and Other Systems."** A. Newman, J. Leung, eds., *Tutorials in Operations Research: Bridging Data and Decision*. Institute for Operations Research and Management Science, Hanover, MD, 180-215.
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- Brown, G., Carlyle, M., Salmerón, J. and Wood, K., 2006, **"Defending Critical Infrastructure,"** *Interfaces*, 36, pp. 530-544.

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