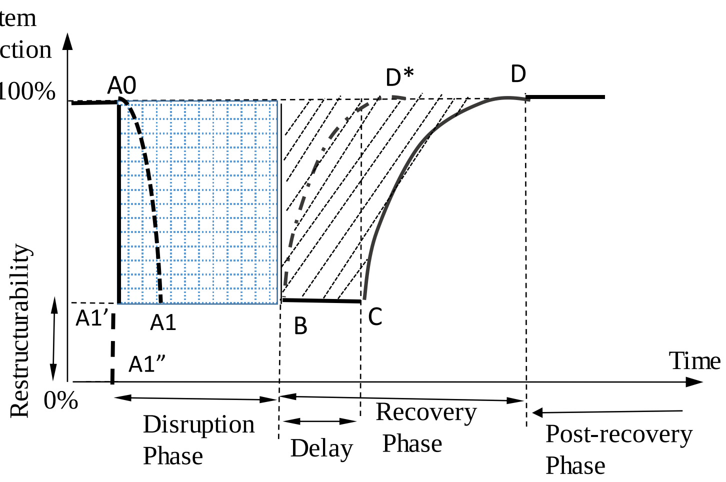
Ira A. Fulton Schools of Engineering
ARIZONA STATE UNIVERSITY

Optimal Post-Disaster Restoration of Power Networks in Puerto Rico



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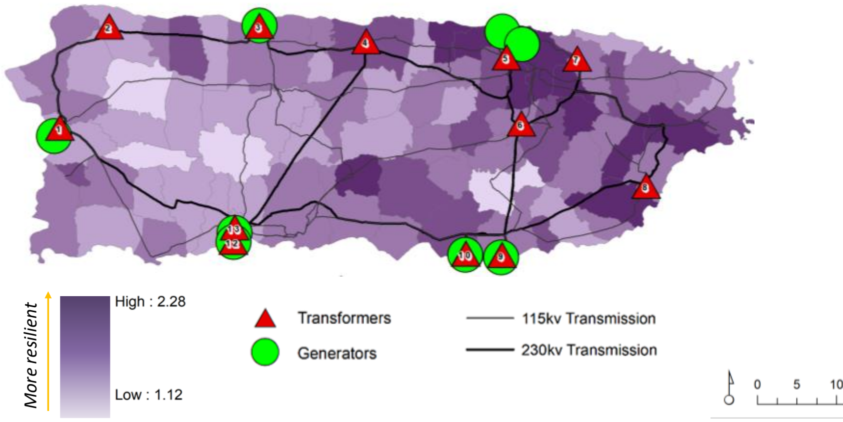
BRI Index for PR Communities
(Overall resilience index determined from census data)



Professors:

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CRISP Symposium: New York, October 24, 2019

Overview

- Modeling Methodology
- Data Collection and Cleaning
- Analysis for whole PR
  - Network Topology
  - Nominal Network
  - Restoration Analysis
- Analysis for western PR
  - Network Topology
  - Nominal Network
- Future Research
- Dynamic Restoration Model

References

[1] PR Power Grid Model, Gustavo Cuello-Polo, Efraín O’Neill-Carrillo, Electrical and Computer Engineering Department, University of Puerto Rico-Mayagüez.

[2] DHS's Homeland Infrastructure Foundation-Level data portal. https://hifld geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines?geometry= 68.682%2C17.734%2C-63.45%2C18.647

[3] Government of Puerto Rico's http://www.gis.pr.gov/descargaGeodatos/Infraestructuras/Pages/Electricidad.aspx

[4] Data published by the Puerto Rico Electric Power Authority in compliance with the Energy Transformation and Relief Act of Puerto Rico. http://energia.pr.gov/wp-content/uploads/2015/09/Estadisticas.pdf

Modeling Methodology

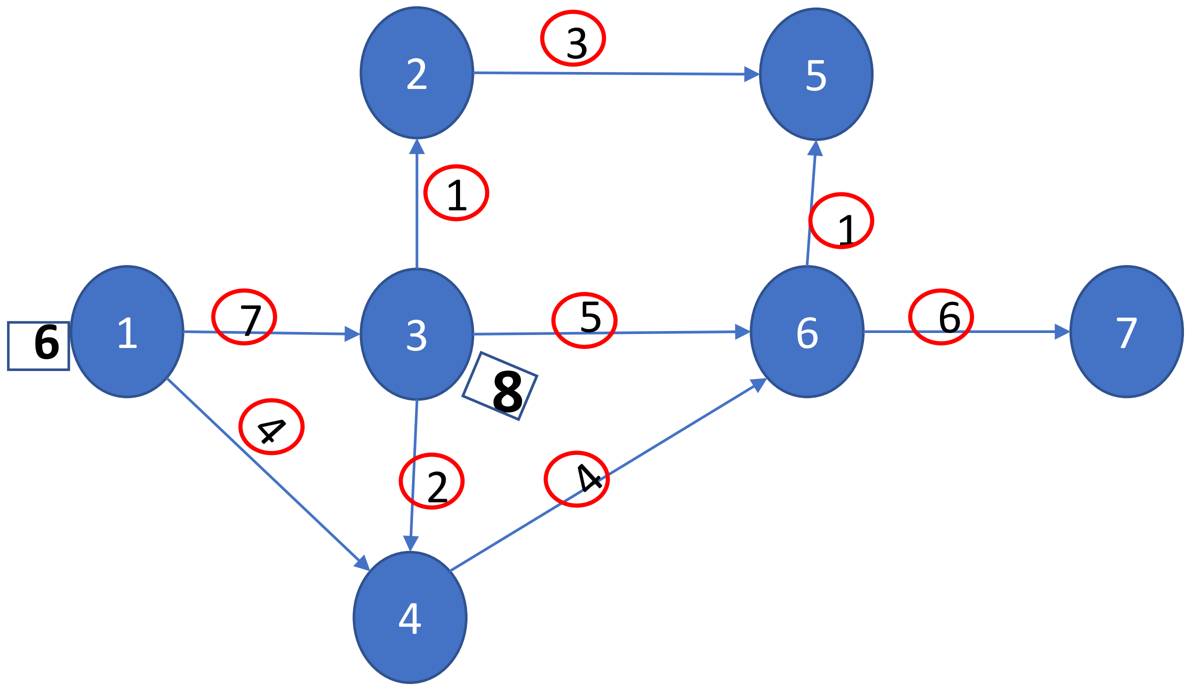
Network flow models to mimic behavior of power networks after disaster

$$\sum_{\{k \in F_i^+\}} f_{\{ki\}}^t + p_i^t - s_i^t - \sum_{\{l \in F_i^-\}} f_{\{il\}}^t = 0 \qquad (1)$$

$$s_i^t \leq d_i^t \, w_i^t \quad (2)$$

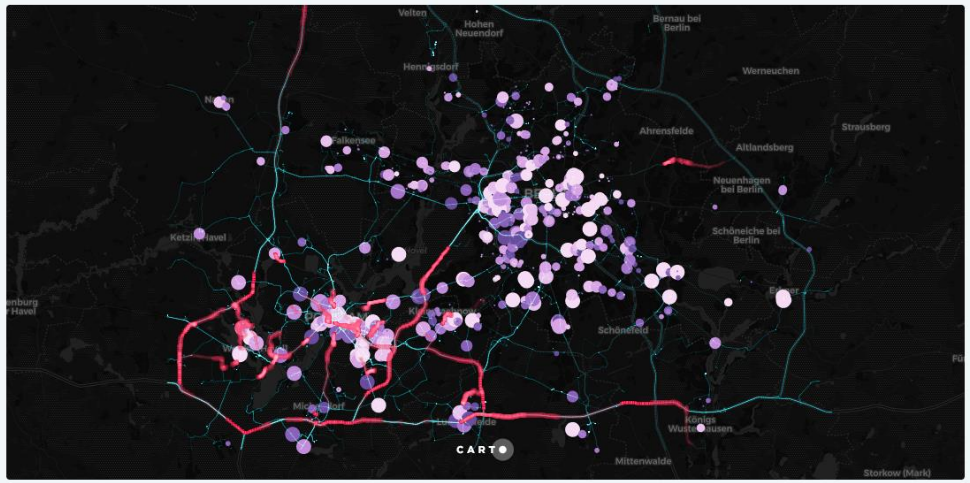
$$p_i^t \leq p_i^{max} \, w_i^t \qquad (3)$$

$$f_{ij}^t \leq f_{ij}^{max} \, w_{ij}^t \qquad (4)$$



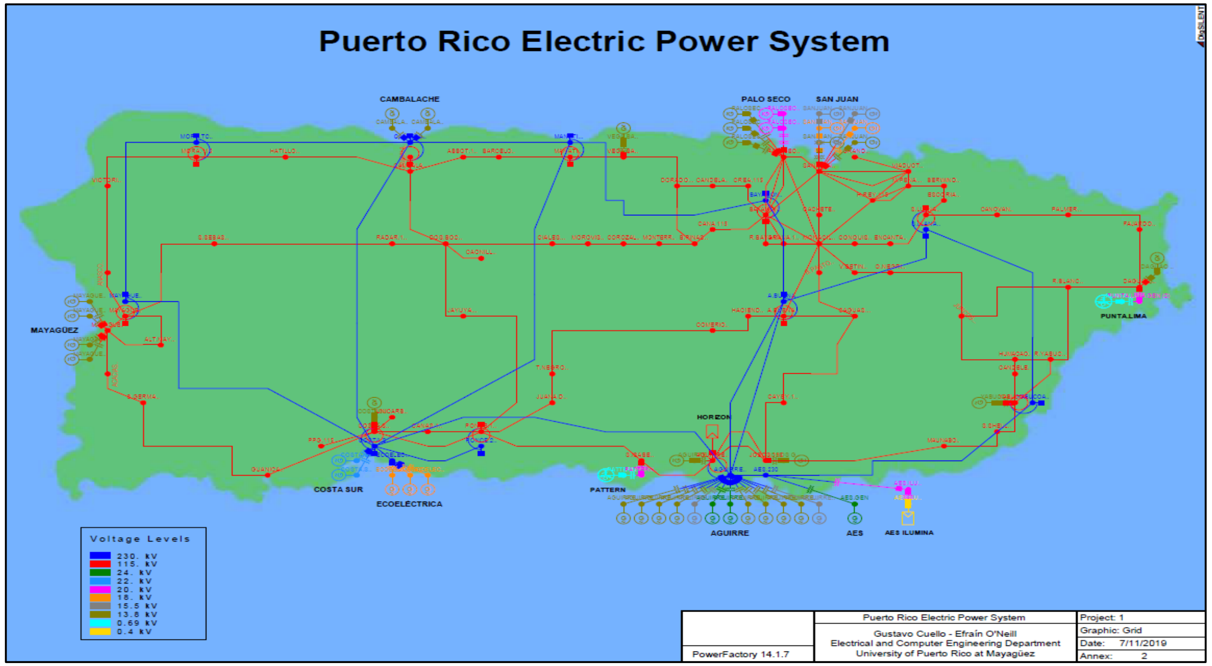
Data Collection

- Started with network in report [1]
  - Conference call to acquire useful resources
- DHS dataset [2]
  - Found to be noisy and inconsistent data
- We finally used government GIS portal [3]
  - Network components were extracted
  - Finalized through conference calls



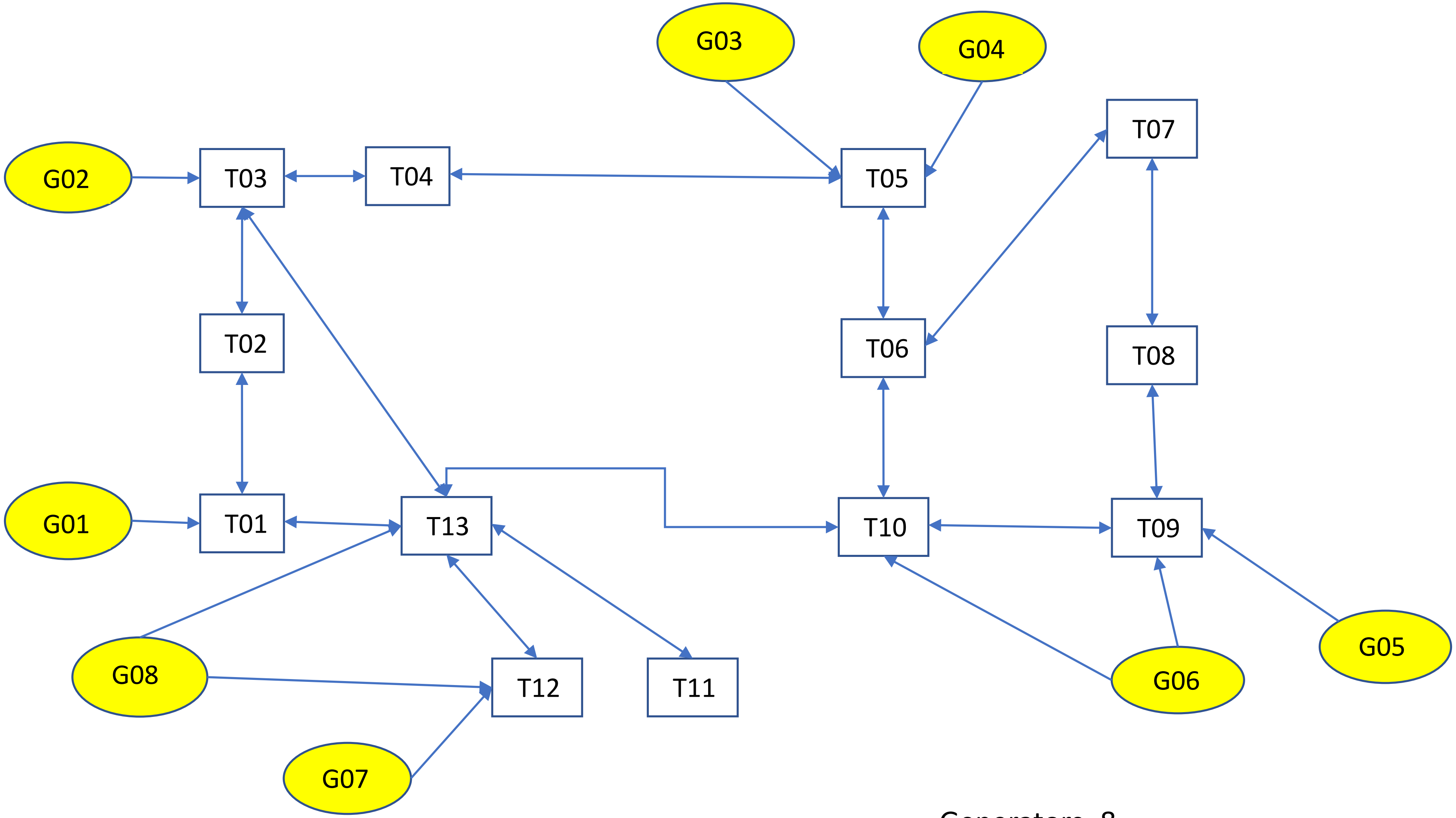
Demand for Electricity in Different Regions

Region Code	Name	Municipalities	Share	Demand (MW)
A1	San Juan	3	23%	558.67
A2	Bayamon	9	13%	315.77
A3	Carolina	7	9%	218.61
A4	Caguas	15	17%	412.93
A5	Ponce E	7	5%	121.45
A6	Ponce W	7	9%	218.61
A7	Arecibo	13	11%	267.19
A8	Mayagüez	15	13%	315.77
Total		76	100%	2,429



http://www.gis.pr.gov/descargaGeodatos/Infraestructuras/Pages/Electricidad.aspx

Whole PR Transmission Network: *Topology*



Generators- 8
High voltage 230 kV transformers- 13

Whole PR Network: *Generators*

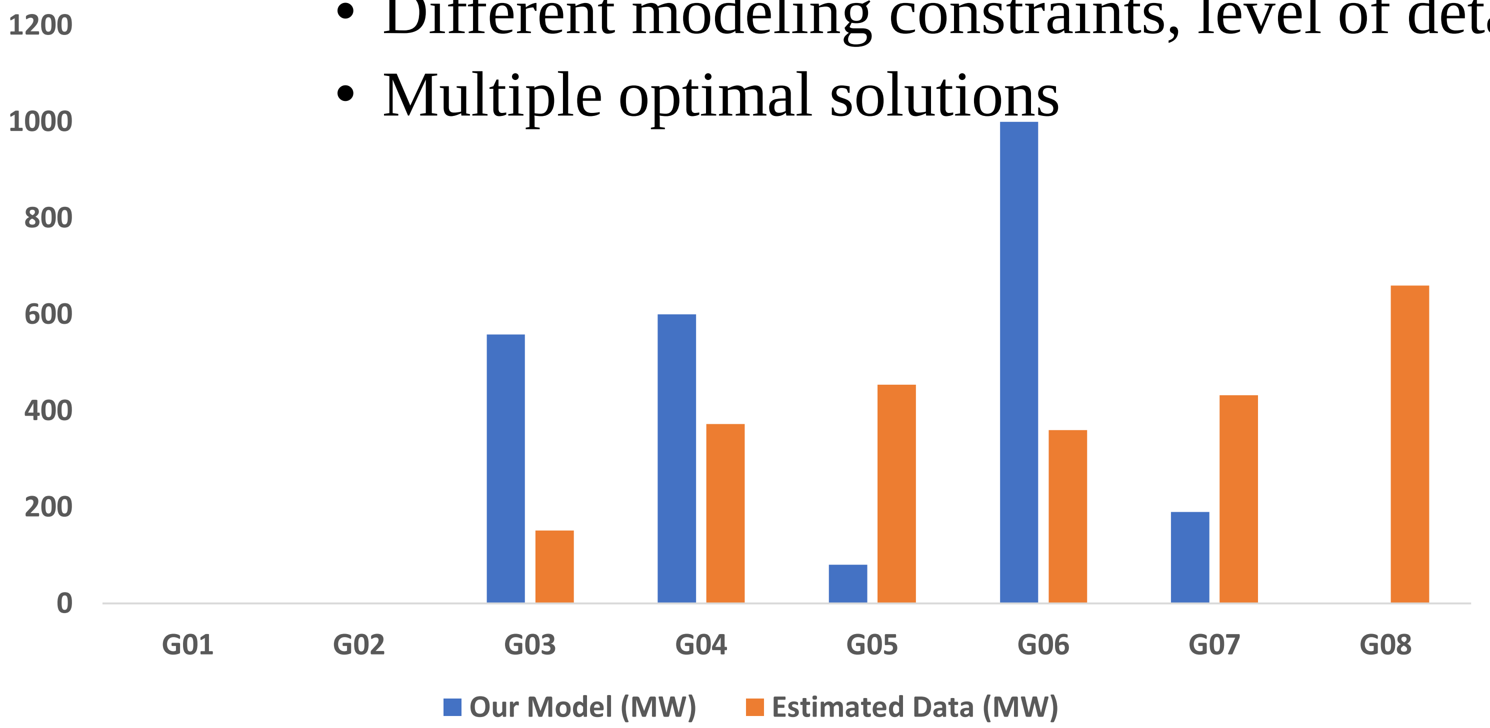
Index	Code	Name	Latitude	Longitude	Region	Capacity (MW)
1	G01	MAYAGUEZ PLANTA	18.22	-67.16	A8	200
2	G02	CAMBALACHE	18.47	-66.7	A7	166
3	G03	PALO SECO	18.46	-66.15	A2	558
4	G04	SJSP	18.43	-66.1	A1	600
5	G05	AES	17.94	-66.15	A5	454
6	G06	Complejo Aguirre	17.95	-66.23	A5	1462
7	G07	ECOELECTRICA	17.98	-66.76	A6	507
8	G08	COSTA SUR	18	-66.75	A6	862
Total Capacity (MW)						4809

Whole PR 230 kV *Transformers*

Code	Name	Region(s)	Load (MW)	HMI
T01	MAYAGUEZ TC	A8	157.88	1.63
T02	MORA TC	A8	157.88	1.63
T03	ARECIBO	A7	133.6	1.72
T04	MANATI	A7	133.6	1.72
T05	BAYAMON	A1, A2, A3	546.52	1.81
T06	AGUAS BUENAS GIS TC	A4	206.46	1.81
T07	SABANA LLANA	A1, A2, A3	546.52	1.81
T08	YABUCOA TC	A4	206.46	1.81
T09	AGUIRRE 1	A5	60.72	1.62
T10	AGUIRRE 2	A5	60.72	1.62
T11	PONCE TC	A6	72.88	1.76
T12	ECOELECTRICA	A6	72.88	1.76
T13	GUAYANILLA	A6	72.88	1.76

Whole PR Network: *Dispatch*

- Dispatch model solved based on discussed topology and parameters
- Our dispatched values as well as ones reported in [2] are shown in Figure 2.
- The differences could be due to:
  - Assumptions made
  - Different modeling constraints, level of details or cost functions
  - Multiple optimal solutions



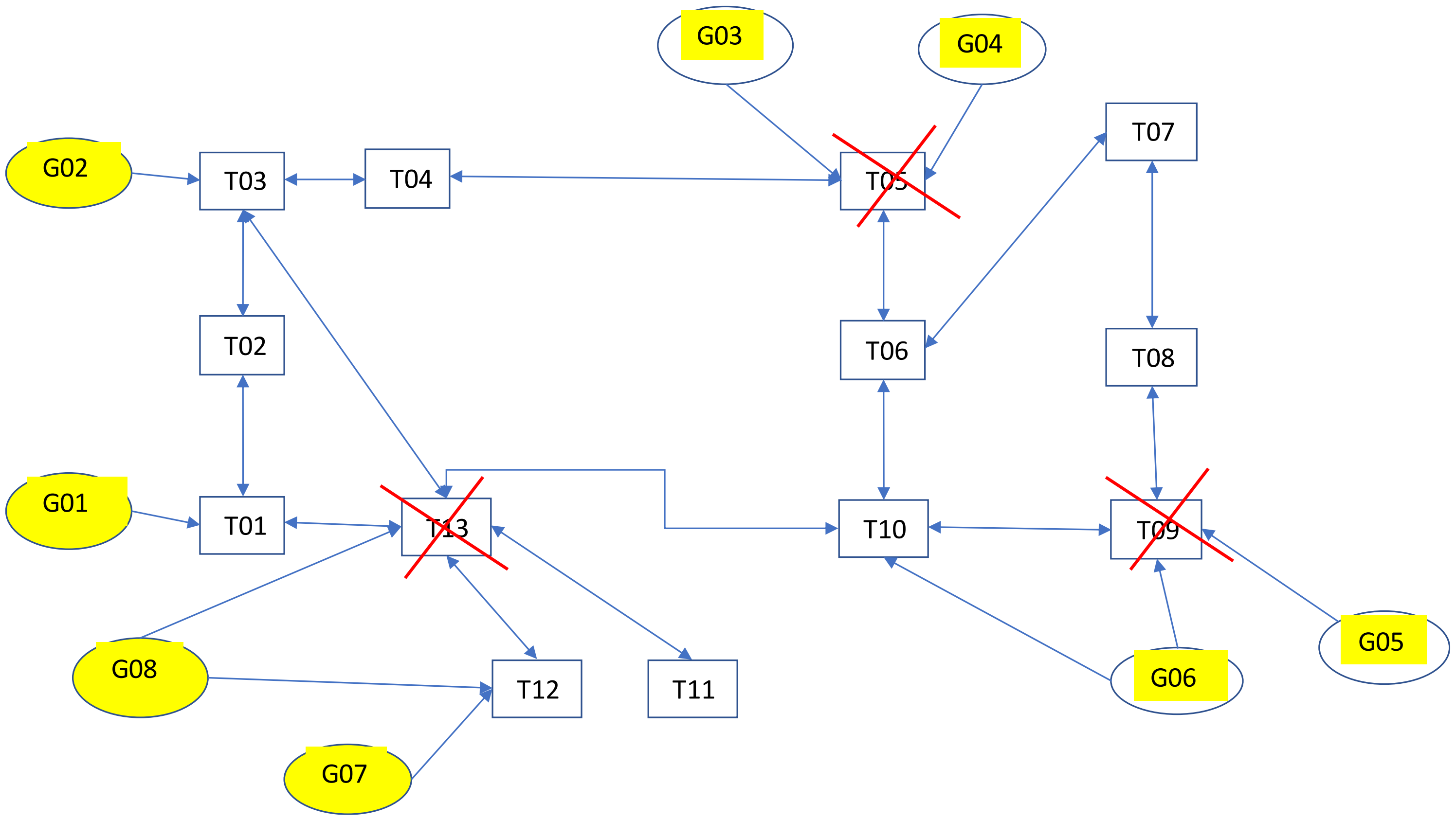
Comparison with a detailed electric power simulation model

Failure Scenarios

Four scenarios:

- T5 fails
- T9 fails
- T13 fails
- All 3 fail

- Calculate figure of merit

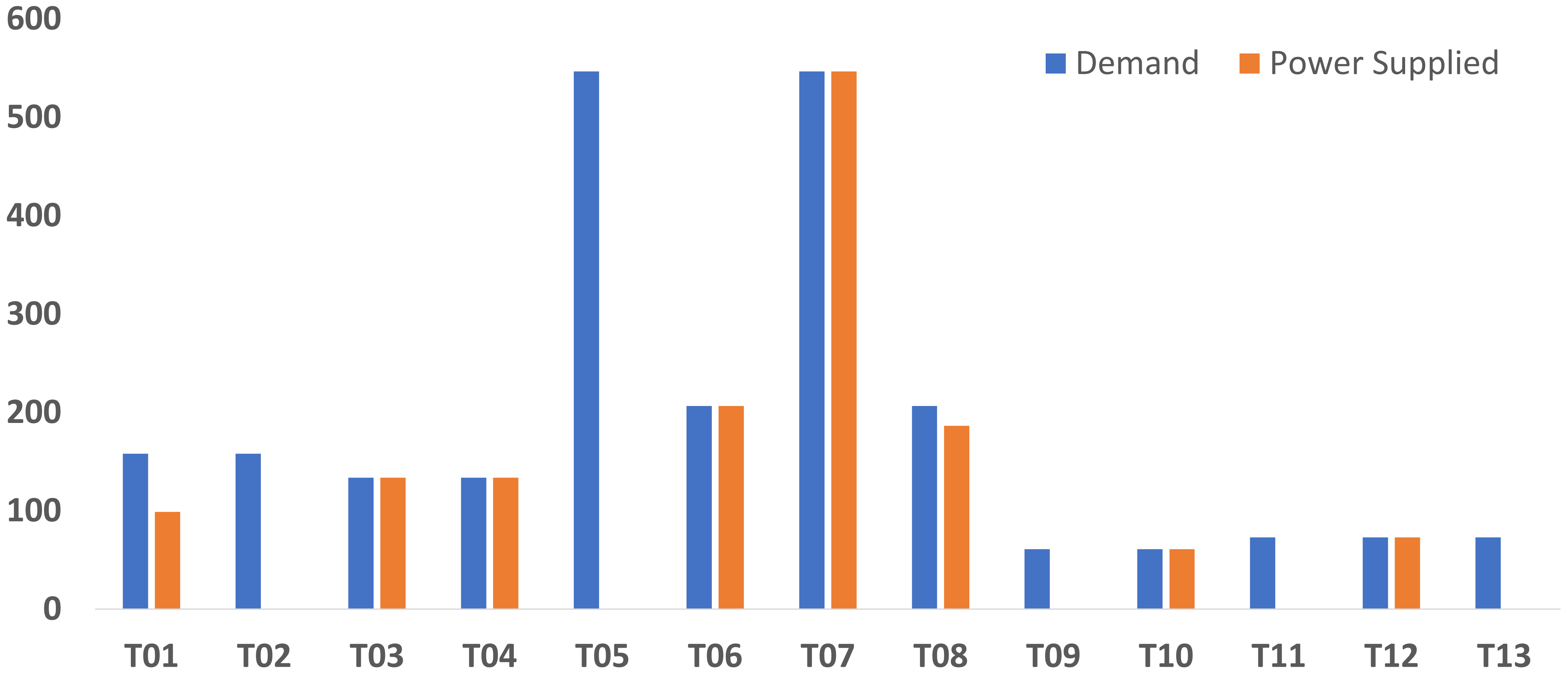


Failure Scenarios: *Loss of Functionality*

Failed Transformers	Supplied Power (MW)	Unmet Load (MW)	Figure of Merit
T09	2,368	61	97.49%
T13	2,283	146	93.99%
T05	1,882	547	77.48%
T05, T09, T13	1,438	991	59.20%

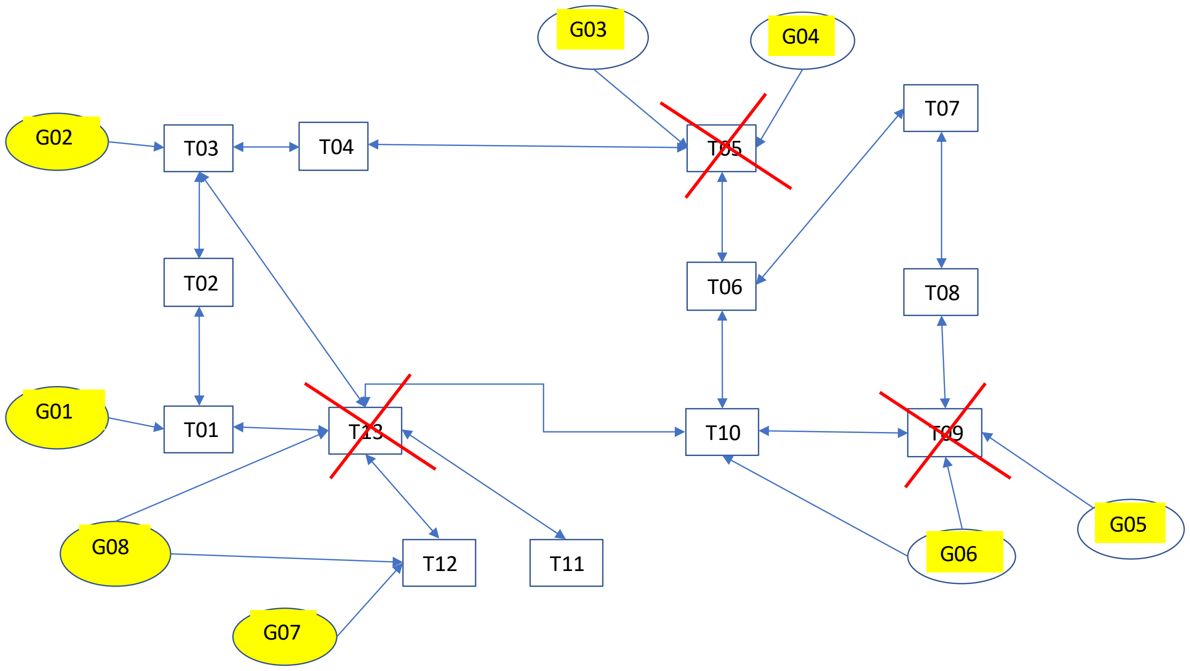
Failure Scenario:

Figure of Merit: 59%



Whole PR Network: *Restoration Analysis*

- Failures in 3 most connected transformers, T05, T09 and T13 was considered.
- Considering outage cost to be $ 20k/MW-hour outage cost for 6 sequences

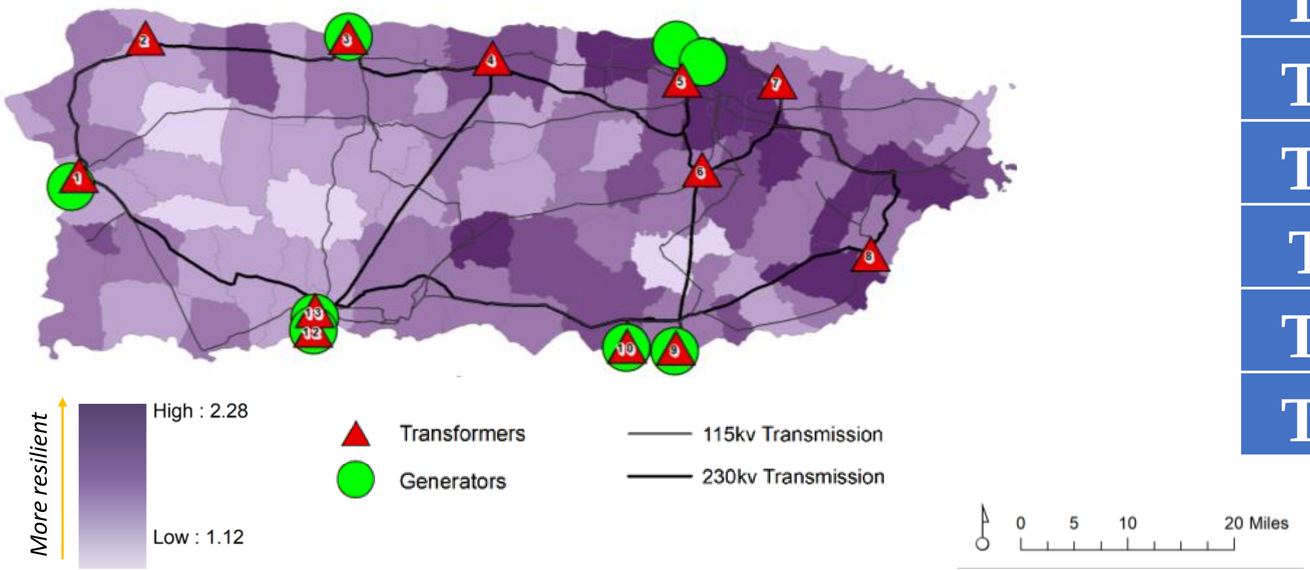


Sequence	Outage Cost (k$)
T05, T09, T13	53,694
T05, T13, T09	**50,293**
T09, T05, T13	81,805
T09,T13, T05	97,835
T13, T05, T09	66,323
T13, T09, T05	85,755

Whole PR Network: Restoration Analysis with BRI

- Analysis redone using BRI indices as multipliers to lost functionality in objective function

BRI Index for PR Communities
(Overall resilience index determined from census data)

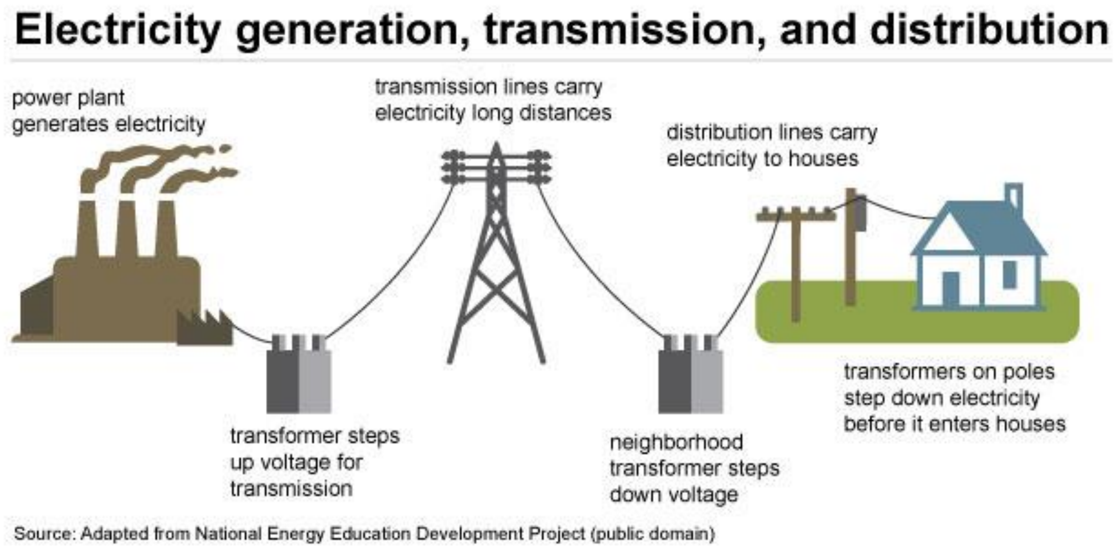


Sequence	Outage Cost (k$)
T05, T09, T13	93,674
T05, T13, T09	87,347
T09, T05, T13	143,453
T09,T13, T05	172,760
T13, T05, T09	116,654
T13, T09, T05	152,287

- In this case, there is no change in the relative impact or ranks. But it cannot be generalized to other failure scenarios.
- We are also looking into improving the integrated objective function

Western PR: Power Network Topology

- Our network model limited to high-voltage (HV) transformers (230 and 115 kV) and transmission lines:
  - 230 kV line transformers reduce voltage to 115 kV lines
  - 115kV step-down transformers supply to distribution lines



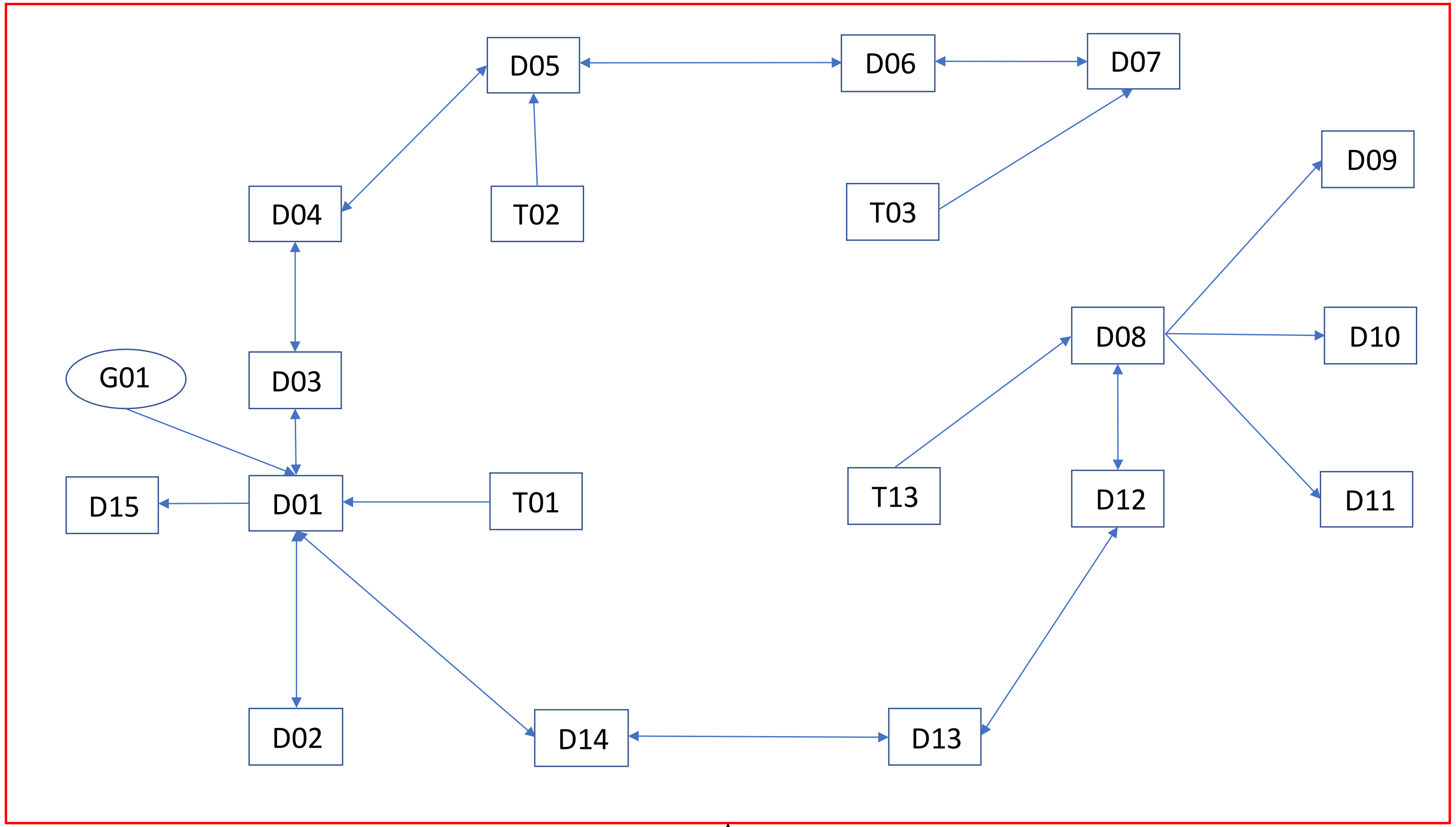
High voltage transmission in Western PR consists of:

- 4 nos. line transformers between 230 kV to 115 kV lines
- 15 nos. step-down transformers from 115 kV to distribution

West PR Networks: 115 kV Transformers

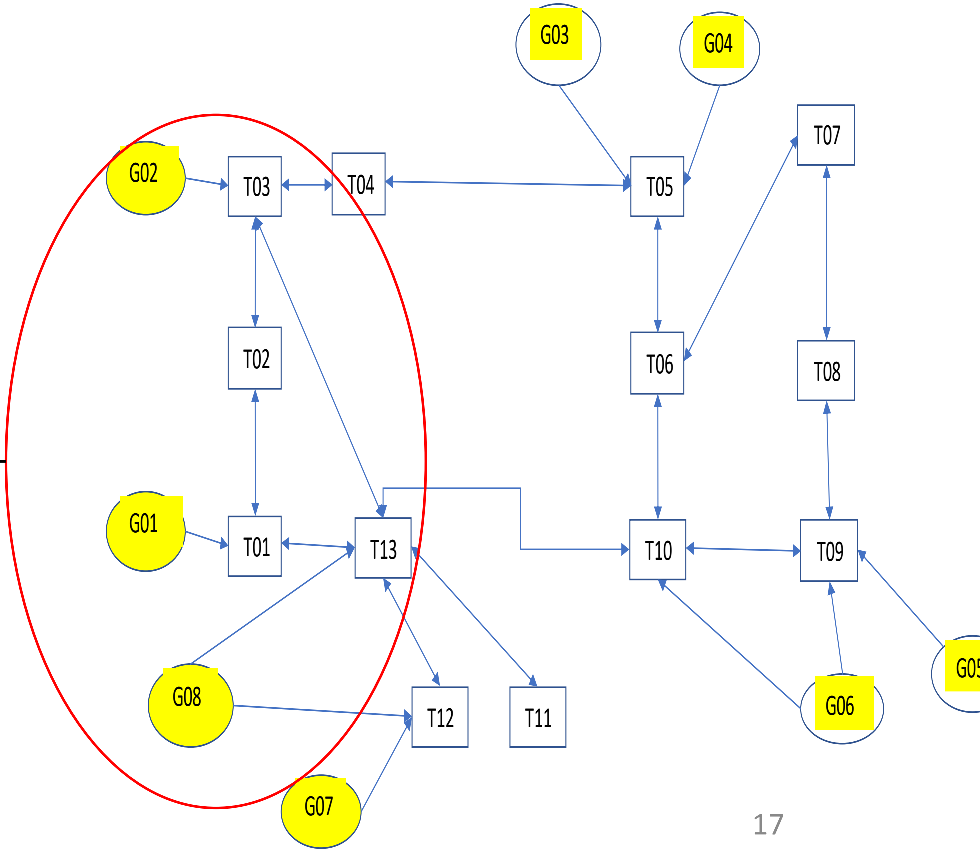
Index	Code	Name	Region	Load (MW)	Municipalities
1	D01	Mayaguez	A8	39.2	Mayaguez, Maricao
2	D02	Altos de Mayaguez	A8	35.1	Mayaguez
3	D03	Anasco	A8	33.2	Anasco, Rincon
4	D04	Victoria	A8	77.4	Aguadilla, Moca, Aguada
5	D05	Mora	A7	28.6	Isabel, Quebradillas
6	D06	Hatillo	A7	37.7	Hatillo, Camuy
7	D07	Cambalache	A7	21.4	Arecibo
8	D08	Costa Sur	A6	28.8	Guayanilla, Yauco
9	D09	Unicarbide	A6	10	Penuelas
10	D10	Canas	A6	60.6	Ponce
11	D11	PPG	A6	5.1	Guanica
12	D12	Guanica	A6	5.1	Guanica
13	D13	San German	A8	52.9	San German, Sabana Grande, Lajas
14	D14	Acacias	A8	33.5	Cabo Rojo, Hormigueros
15	D15	San Sebastian	A8	37.1	San Sebastian, Lares, Las Marias

Peak electric loads at each step-down transformer node known for a typical hot summer day



Network Topology: West PR

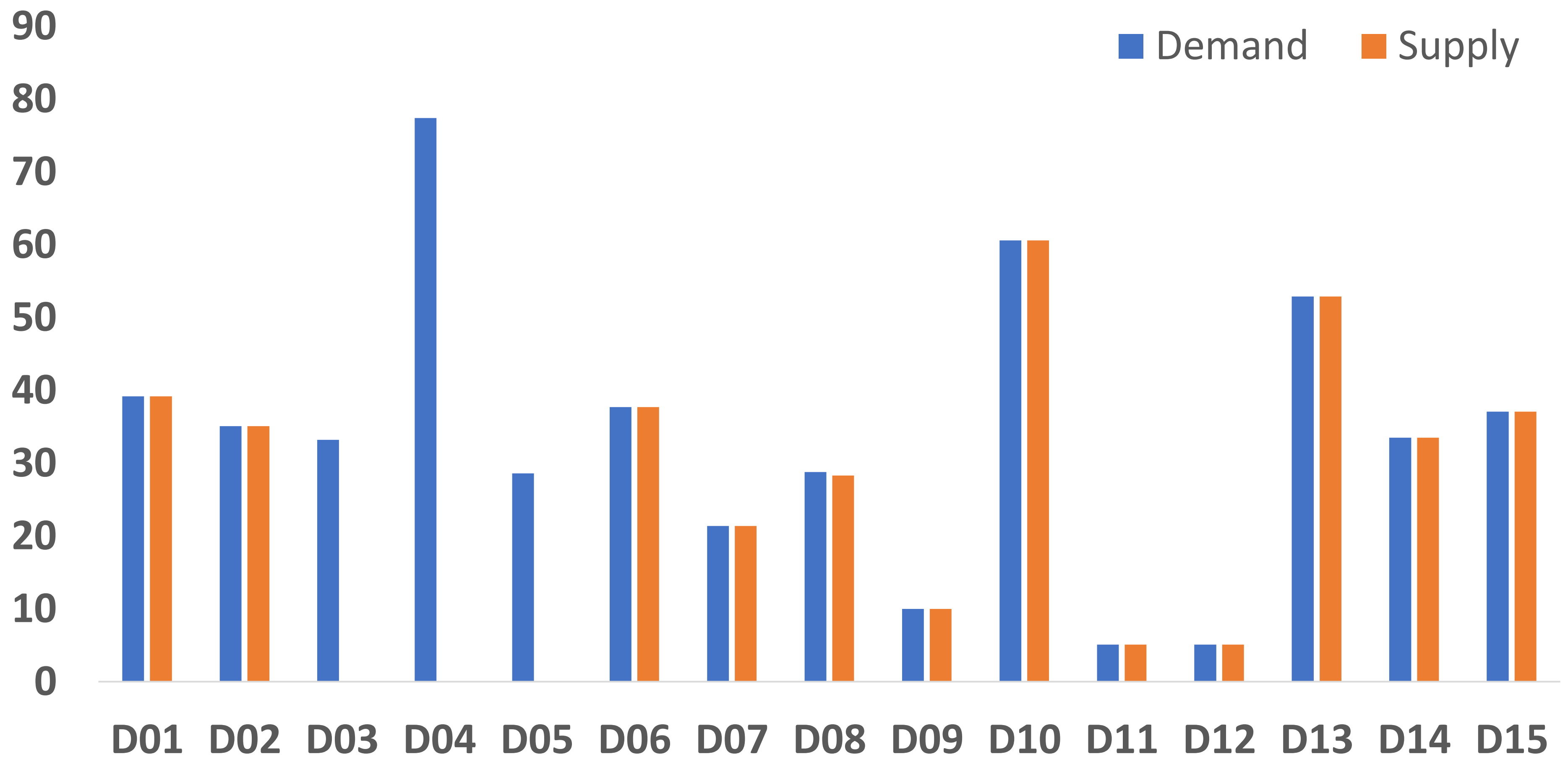
Network Topology: Whole PR



Failure Scenario Simulation:

Assuming failure in T05, T09 and T13

Figure of merit: 72%



Allied Ongoing Research: Dynamic Restoration

Problem Statement

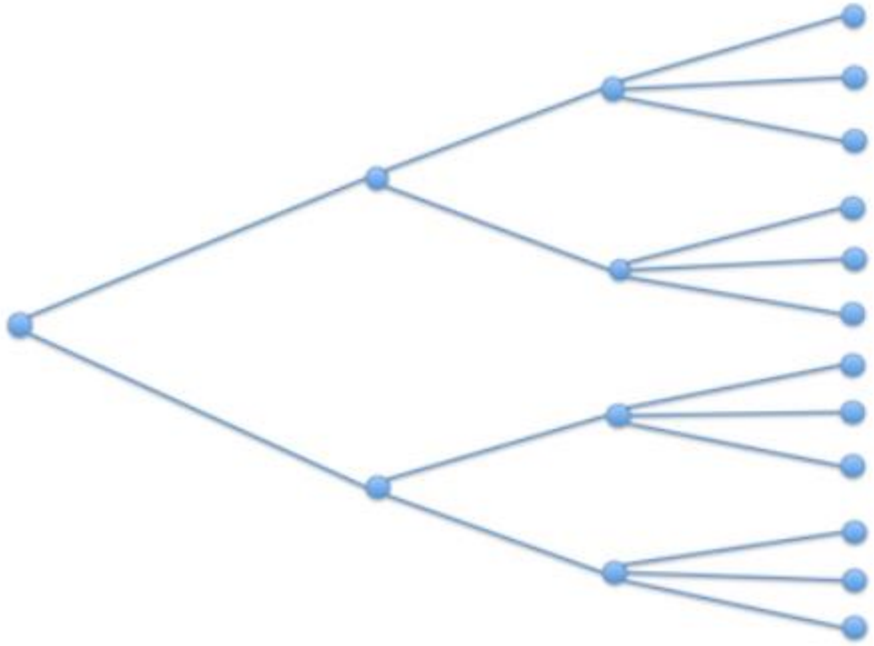
- As a hurricane propagates, it damages the power network
  - Failures in distribution, we consider high-voltage loads.
  - Path and wind speed can be formulated as stochastic scenarios.
- Repair teams can be prepositioned or assigned to failed loads.
- Input to model:
  - Network and repair crew state
  - Available Transportation network
  - Updated failure scenarios
- Outputs (in real-time):
  - Optimal prepositioning!
  - Optimal assignment!

Dynamic Restoration: Problem Formulation

- The problem can be formulated as a stochastic dynamic program
- In simple words, the best action is an action that minimizes:

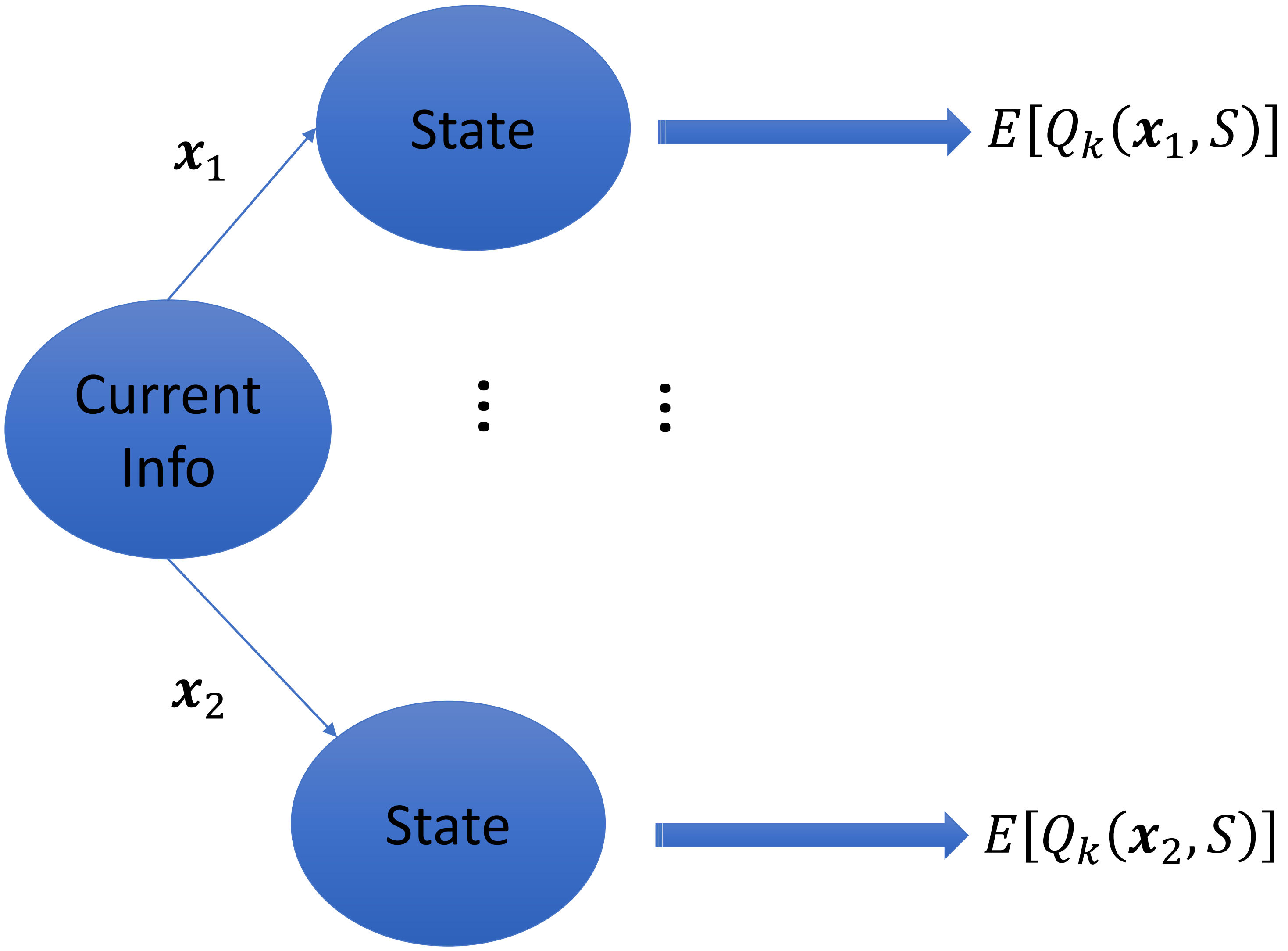
Cost at time period t + average of costs over time periods t+1, t+2, ….

- We should explore the whole scenario tree



- This could take forever!
- Solution: **Rollout Heuristic Algorithms**

Dynamic Restoration: Rollout Heuristic



- Current system state, states in next stage are generated.
- Starting from each final state, a set of failure realizations is generated.
- A heuristic policy is adopted for each realization and future cost is evaluate.
- Expected future cost is the average of these realized costs.
- Action that minimizes the total cost is selected.

Dynamic Restoration: Rollout Heuristic