PEER

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

UILLIS:

Urban Infrastructures and Lifelines Interaction of Systems

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PEER Center

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Agenda

- Summary of research
- System Reliability
- Multi-Hazard System Reliability
- Multistate System Reliability for Required Demand
- Interdependent System Reliability
- Urban Infrastructure and Lifeline Interactions of Systems (UILLIS)

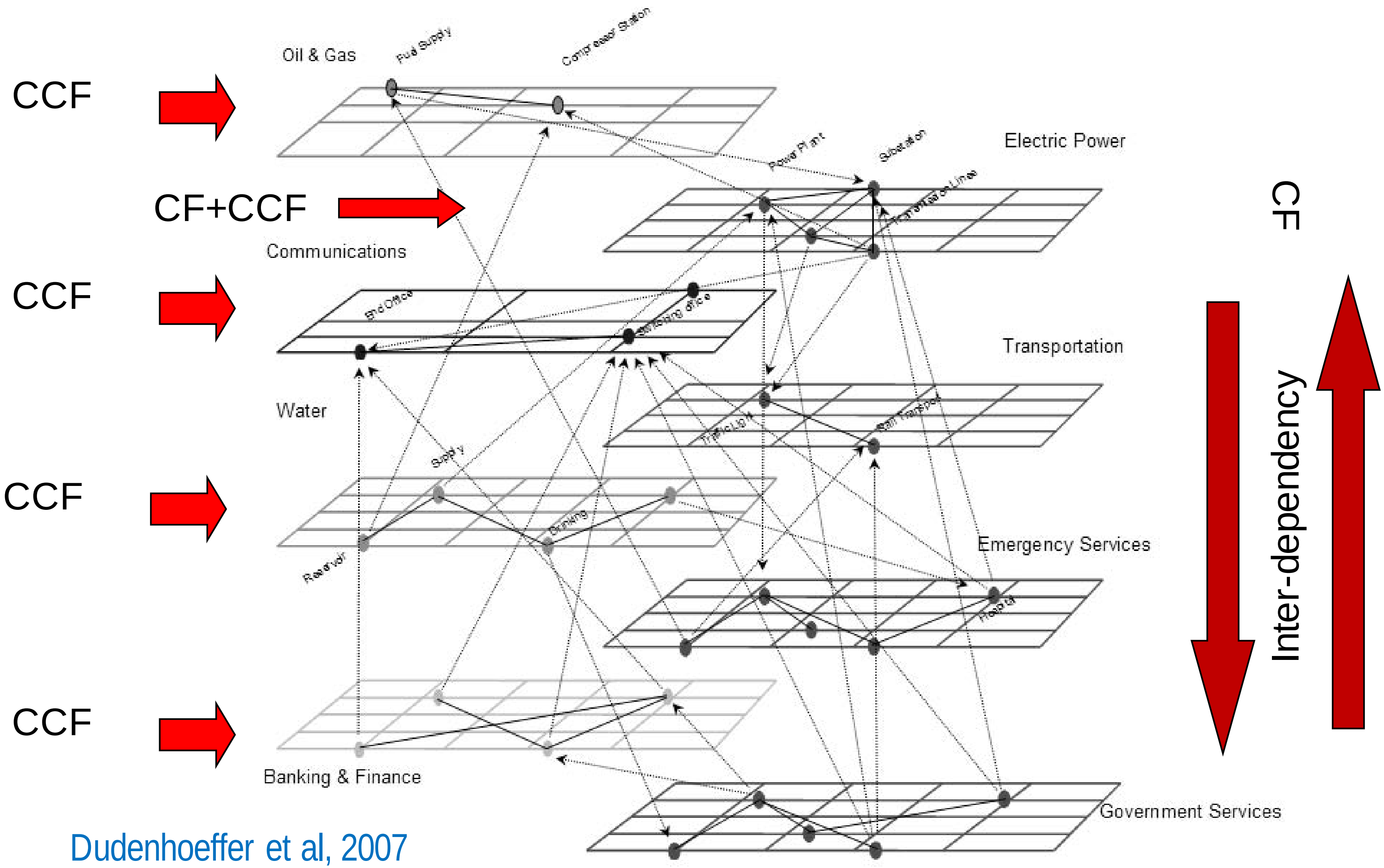
Summary of research

- Infrastructure risk should be modeled with accounting of interdependencies, cascading or common cause failures, collocation or other effects.

- Capture and quantify the complexities of large inter-dependent urban infrastructure.

- Such “system of systems” have applications far beyond urban infrastructure.

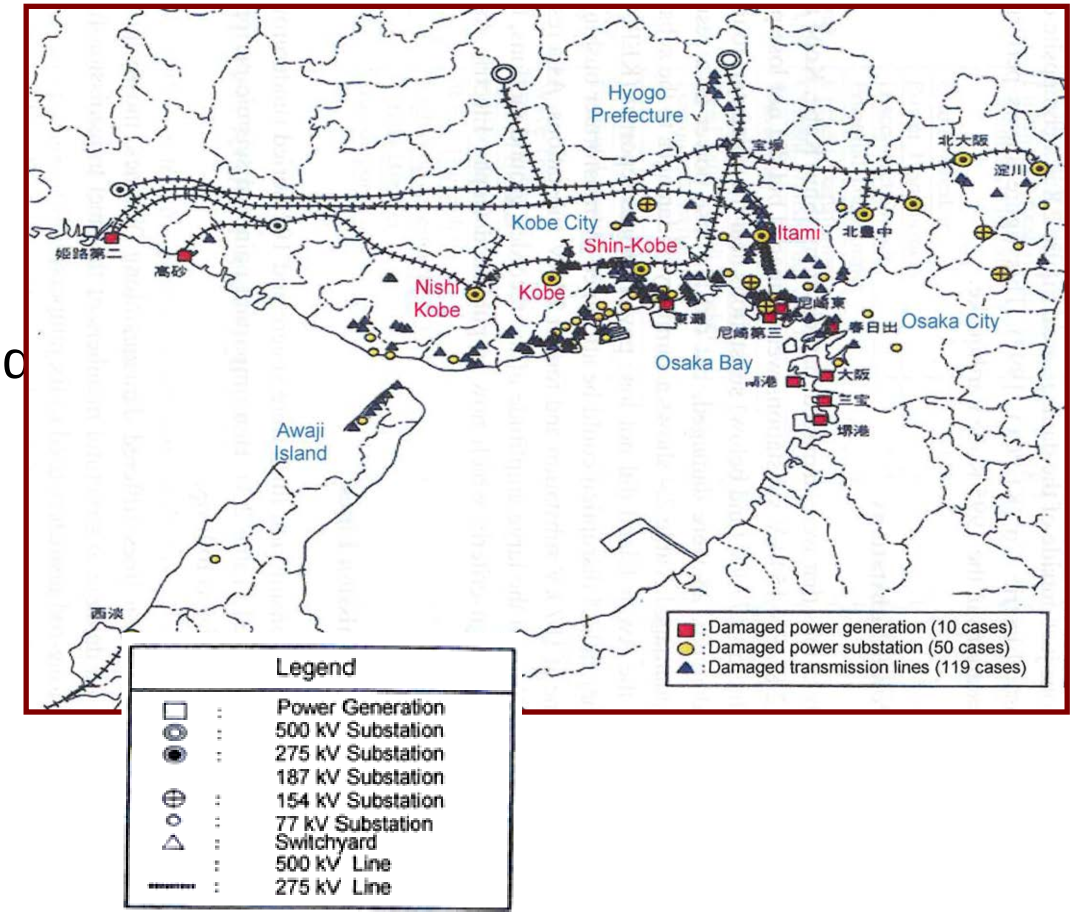
Failures: common-cause (CCF) and cascading failures (CF)



Dudenhoeffer et al, 2007

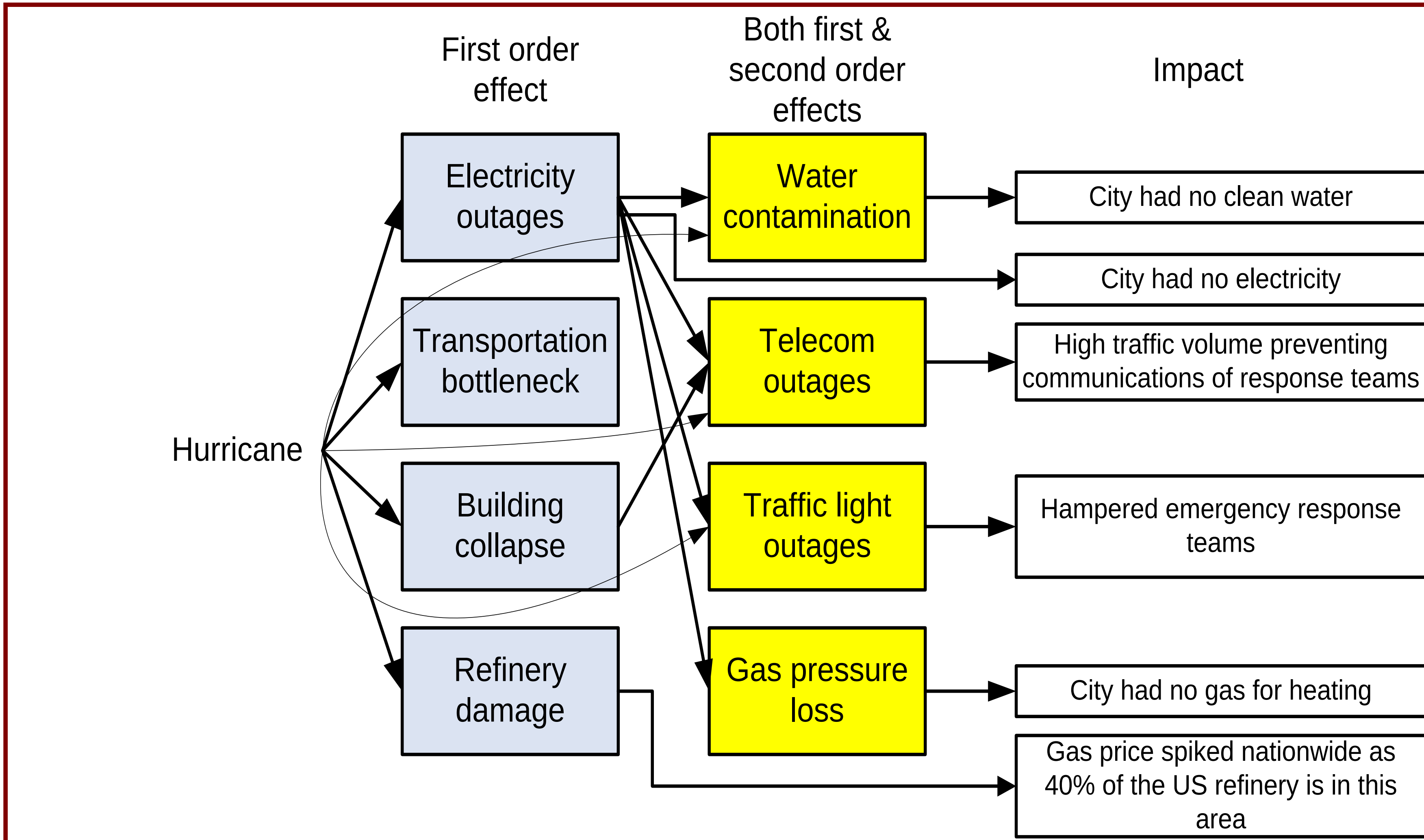
Kobe: CF as a result of CCF

- Malfunction of traffic signals
- Loss of satellite emergency communications
- Hospital shutdowns
- Loss of water filtration plants and pump stations
- Loss of water and elevators in high-rises
- Fire ignitions (gas leaks and electricity sparks)
- Lack of heating at shelters



Power outage due to the 1995 Kobe EQ. (KEPCO, 1997)

Katrina: lifeline interactions example



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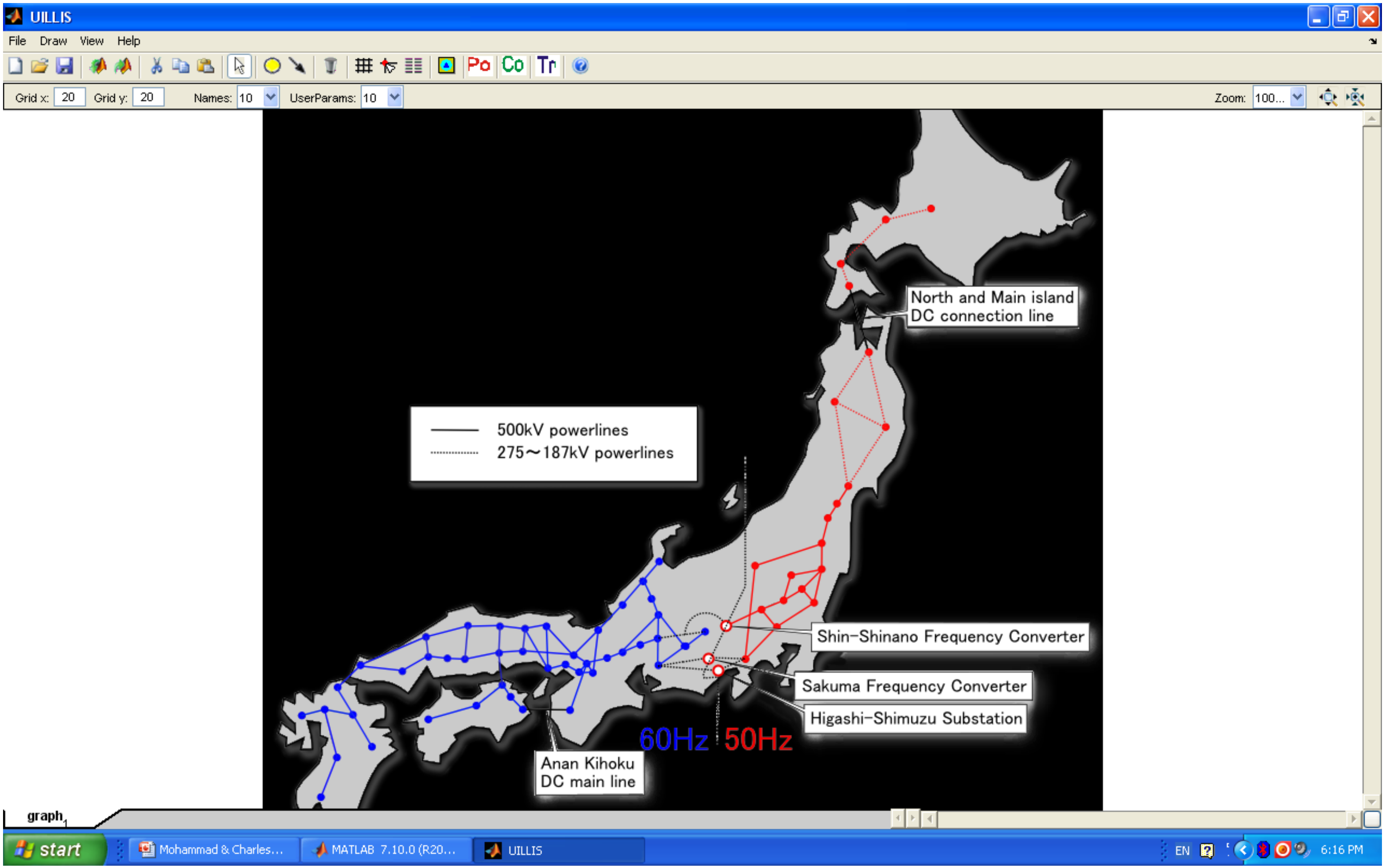

UILLIS
File Draw View Help
Grid x: 20 Grid y: 20 Names: 10 UserParams: 10
Zoom: 100...
500kV powerlines
275～187kV powerlines
North and Main island DC connection line
Shin-Shinano Frequency Converter
Sakuma Frequency Converter
Higashi-Shimuzu Substation
Anan Kihoku DC main line
60Hz
50Hz
graph1
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MATLAB 7.10.0 (R20...
UILLIS
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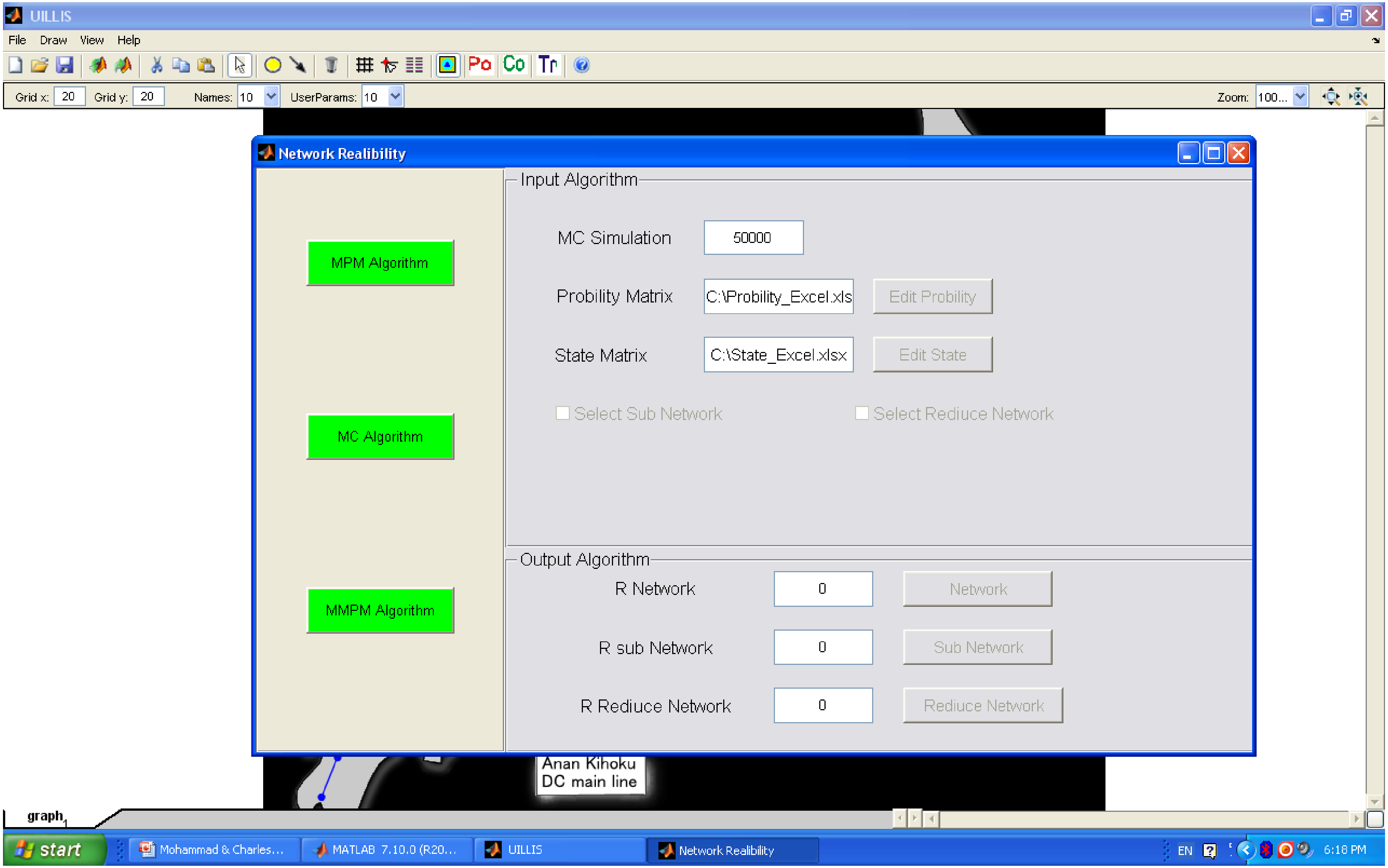
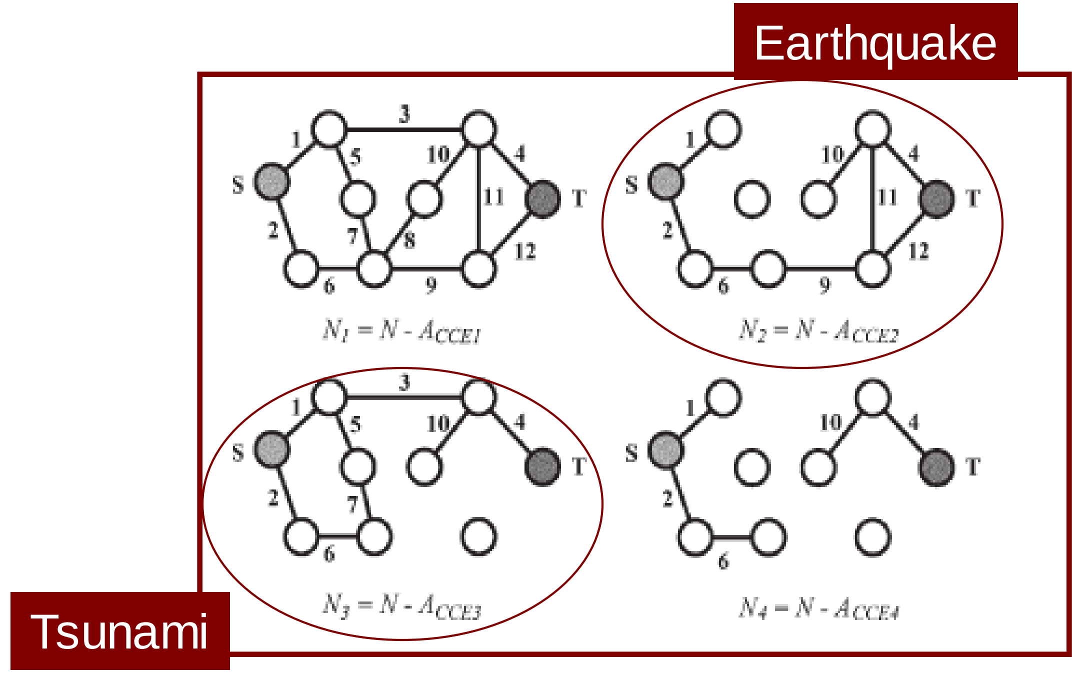
Algorithms for system reliability



Algorithm 1: multi-hazard system reliability

- Hazards - events
  - ➢ Tsunami, 3, 5, 7, & 8
  - ➢ Earthquake, 8, 9, 11, & 12
- Hazards – probability of occurrence
  - ➢ Tsunami, 0.003
  - ➢ Earthquake, 0.002



$$\Pr(CCE_1) = (1 - P_{E_1})(1 - P_{E_2})$$
Prob. no failure due to CCF

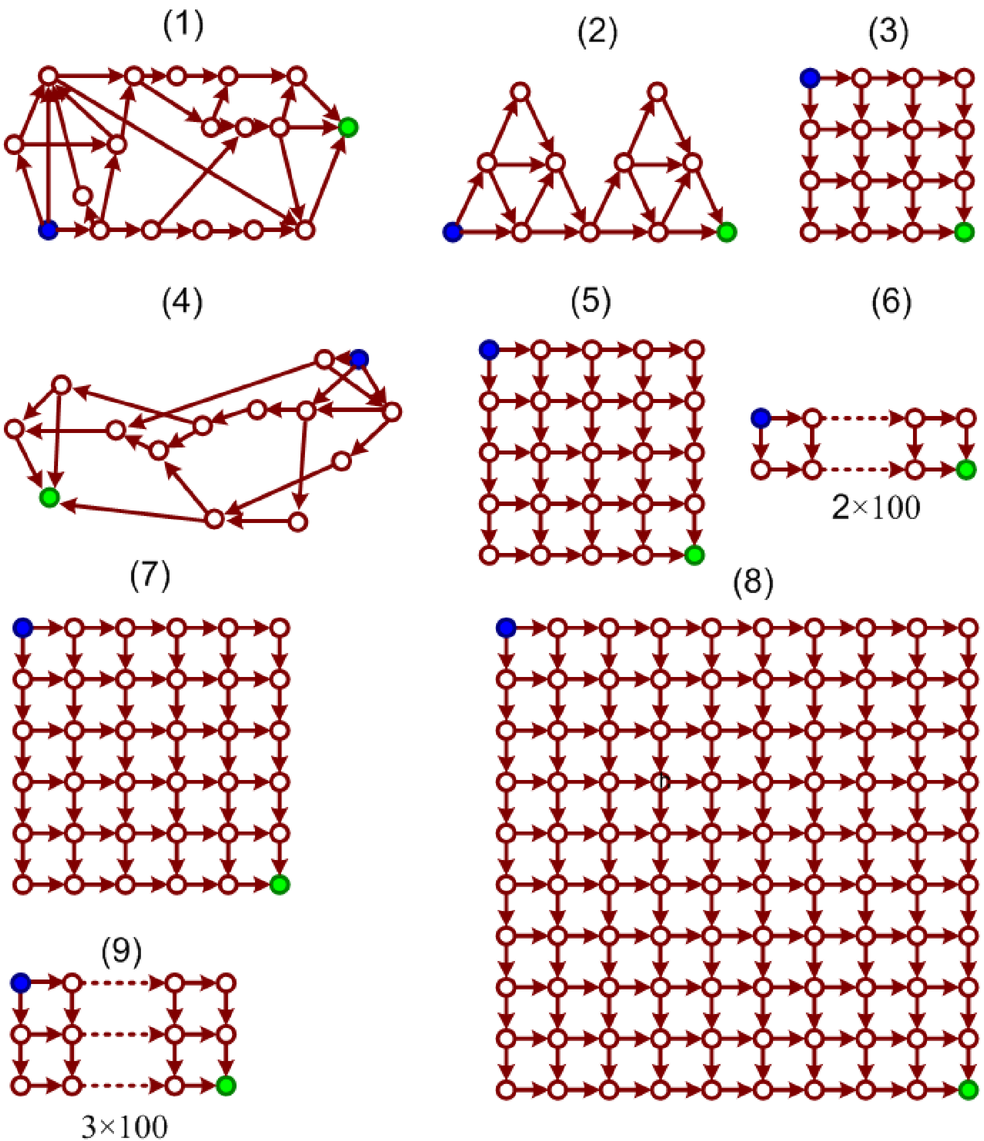
$$\Pr(CCE_2) = P_{E_1}(1 - P_{E_2})$$
Prob. of Tsunami, but no earthquake

$$\Pr(CCE_3) = (1 - P_{E_1})P_{E_2}$$
Prob. of earthquake, but no tsunami

$$\Pr(CCE_4) = P_{E_1}P_{E_2}$$
Prob. that both earthquake and tsunami happen

$$P_F = \sum_{i=1}^{2^m}\left[\Pr(F \mid CCE_i) \bullet \Pr(CCE_i)\right]$$
Multi-hazard Prob. of system failure

Algorithm 2: MPM (minimal path method): system connectivity



Network	Minpath	Run time-minpath (*seconds*)	Reliability
1	44	0.028	0.2966
2	36	0.027	0.2065
3	20	0.026	0.1778
4	15	0.026	0.2781
5	70	0.033	0.1184
6	100	1.723	0.0
7	252	0.065	0.0903
8	48620	238.682	0.020
9	5050	76.297	0.0

Algorithm 3: Monte Carlo system reliability very large network

- **binary**

x	e_1	e_2	e_3	e_4	e_5
x_1	1	1	0	0	0
x_2	1	0	1	0	1
x_3	0	1	1	1	0
x_4	0	0	0	1	1

- **multistate**

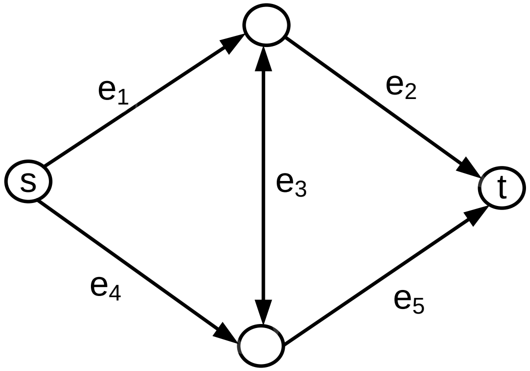
x	e_1	e_2	e_3	e_4	e_5
x_1	3	2	0	0	0
x_2	2	0	1	0	1
x_3	0	2	3	1	0
x_4	0	0	0	1	3
….					

$$X_s = (x_1, x_1, x_1 \ldots, x_{|E|})$$

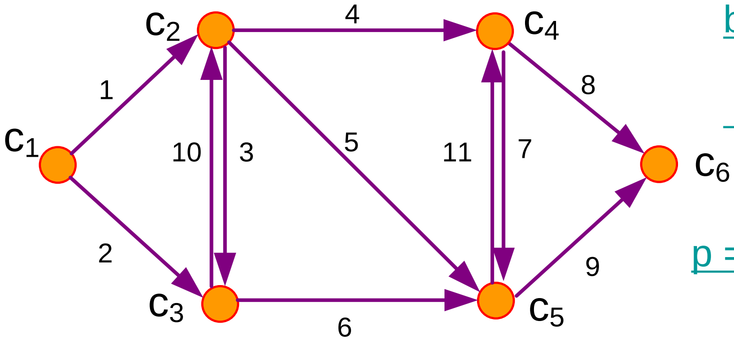
$$\mu(x) \geq d$$

$$Q(system \quad success)$$

$$R = \frac{Q}{N}$$



Algorithm 4: Multistate reliability - communication



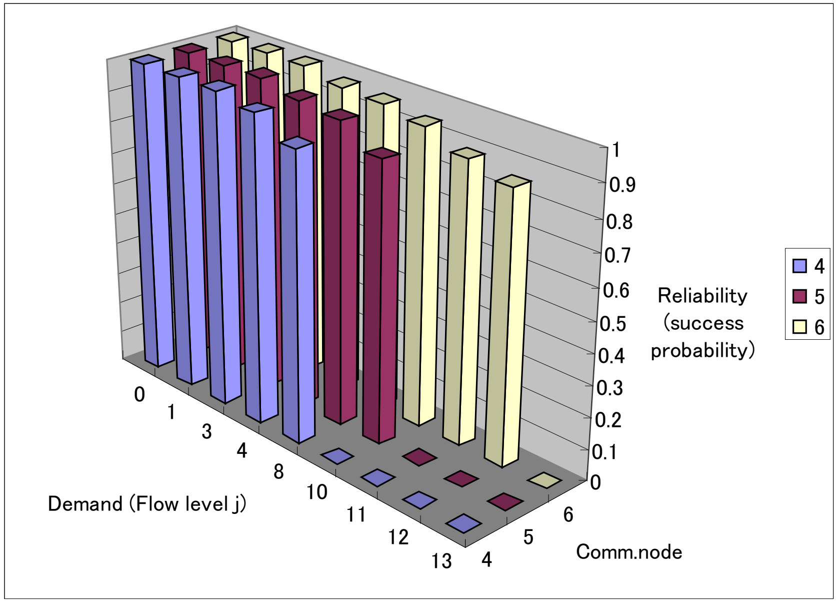
State vector of components:

b={[0,3,4,8],[0,3,4,6],[0,3],[0,3,4],[0,3],[0,3,6],[0,3],[0,3,4,6],...
[0,3,4,8],[0,3],[0,3]}

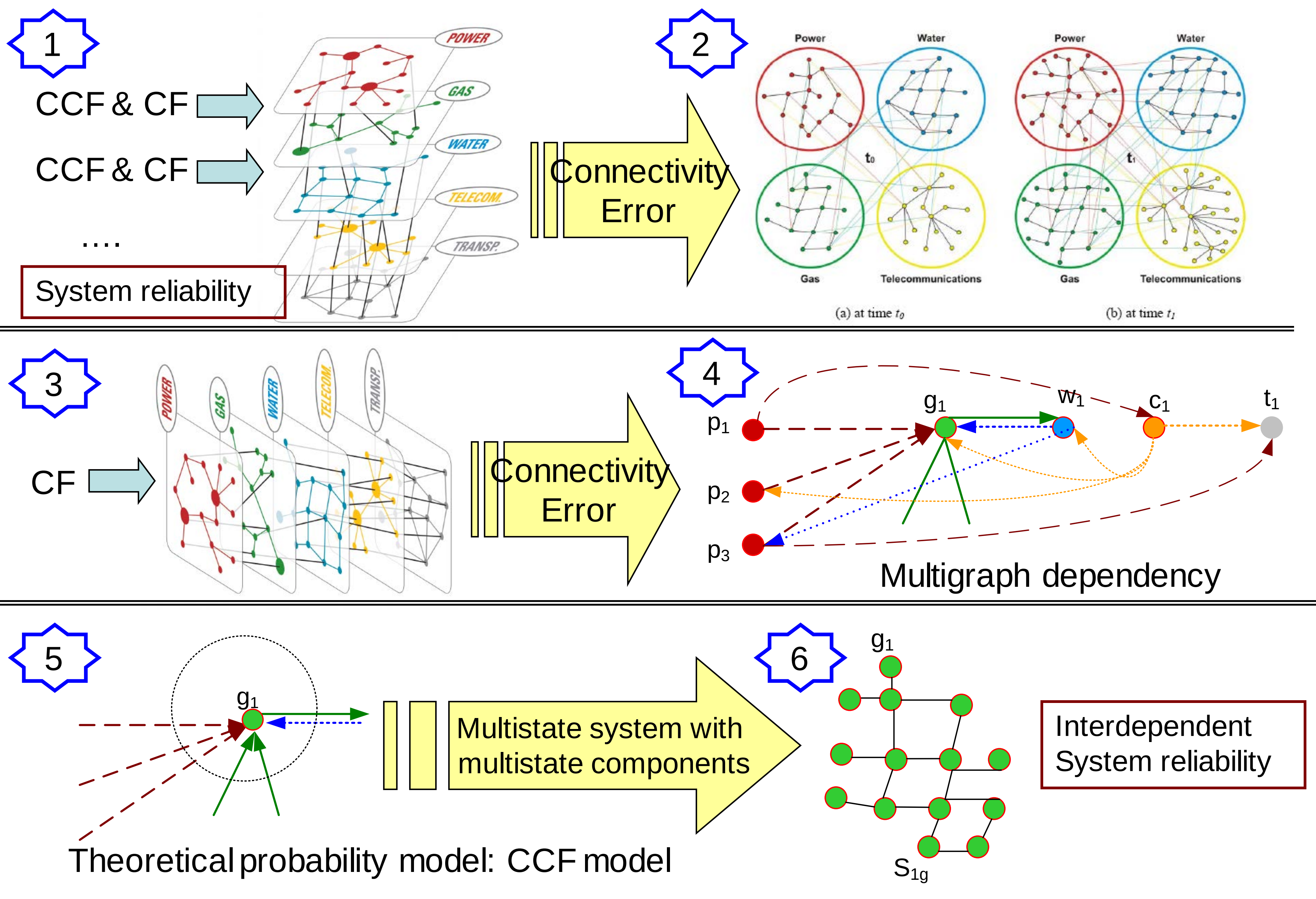
Probability vector of components:

p = {[0.005 0.005 0.01 0.98],[0.02 0.01 0.015 0.955],[0.02 0.98],...
[0.01 0.015 0.975],[0.02 0.98],[0.005 0.02 0.975],[0.01 0.99],...
[0.01 0.015 0.005 0.97],[0.02 0.01 0.01 0.96],[0.02 0.98],[0.01 0.99]}

Demand	Reliability node 4	Reliability node 5	Reliability node 6
0	1	1	1
1	0.9999	0.9999	0.9999
3	0.9991	0.9990	0.9992
4	0.9759	0.9735	0.9739
8	0.9162	0.9577	0.9651
10	0.0	0.8889	0.9429
11	0.0	0.0	0.8912
12	0.0	0.0	0.8576
13	0.0	0.0	0.0



Algorithm 5: Interdependent system reliability



Types of interdependencies

Probability of occurrence:

- *s*-independent

$$P(E_1) = (1 - P_{e_1})(1 - P_{e_2})$$ Prob. Of no failure due to *e*

$$P(E_2) = P_{e_1}(1 - P_{e_2})$$ Prob. of e_1, but no e_2

$$P(E_3) = (1 - P_{e_1})P_{e_2}$$ Prob. of e_2, but no e_1

$$P(E_4) = P_{e_1}P_{e_2}$$ Prob. that both e_1 and e_2

- *Mutual exclusive*

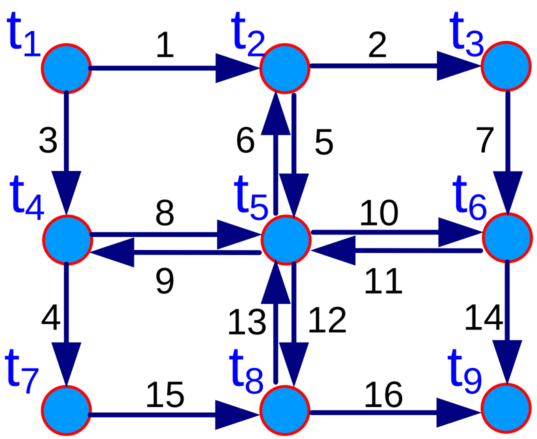
$$P(E_1) = 1 - P_{e_1} - P_{e_2}$$
$$P(E_2) = P_{e_1}$$
$$P(E_3) = P_{e_2}$$
$$P(E_4) = 0$$

- *s*-dependent

$$P(E_1) = (1 - P_{e_1})(1 - q)$$
$$P(E_2) = P_{e_1}(1 - p)$$
$$P(E_3) = (1 - P_{e1}).q$$
$$P(E_4) = P_{e1}.p$$

$$P(e_2 / e_1) = p$$
$$P(e_2 / \sim e_1) = q$$

Example: transportation network



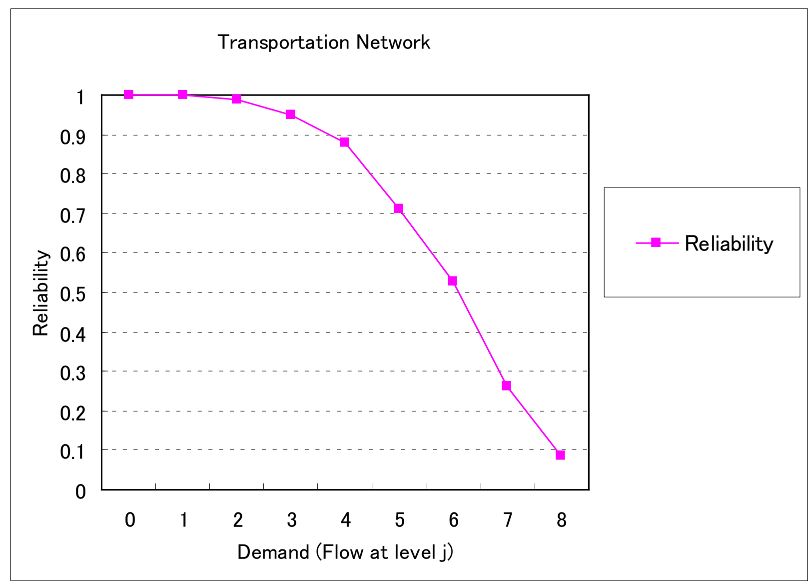
State vector of components:

b={[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],...
[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],...
[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],[0,1,2,3,4],...
[0,1,2,3,4]}

Probability vector of components:

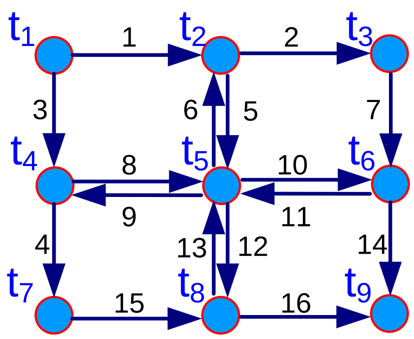
```
p = {[0.05 0.05 0.1 0.2 0.60],[0.05 0.05 0.15 0.25 0.50]
     [0.05 0.1 0.15 0.2 0.50],[0.05 0.05 0.10 0.20 0.60]
     [0.05 0.05 0.15 0.25 0.50],[0.05 0.1 0.15 0.2 0.50]
     [0.05 0.05 0.1 0.2 0.60],[0.05 0.05 0.15 0.25 0.50]
     [0.05 0.1 0.15 0.2 0.50],[0.05 0.05 0.10 0.20 0.60]
     [0.05 0.05 0.15 0.25 0.50],[0.05 0.1 0.15 0.2 0.50]
     [0.05 0.05 0.1 0.2 0.60],[0.05 0.05 0.15 0.25 0.50]
     [0.05 0.1 0.15 0.2 0.50],[0.05 0.05 0.1 0.2 0.60]};
```

Demand	Reliability node 9, R_9	Probability of failure $(P_9=1-R_9)$
0	1	1
1	0.9990	0.9990
2	0.9890	0.9890
3	0.9490	0.9490
4	0.8770	0.8770
5	0.7100	0.7100
6	0.5260	0.5260
7	0.2600	0.2600
8	0.0870	0.0870

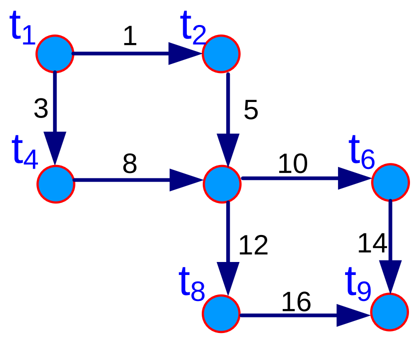


Reduced networks – conditional probabilities

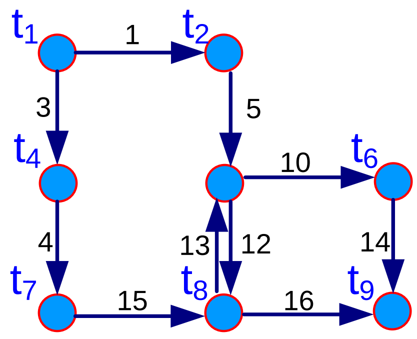
- *transport*
- *power*
- *communication*
- *pow.+ comm.*



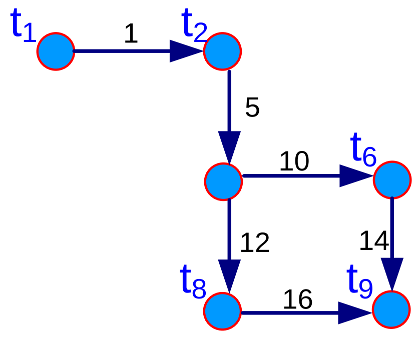
N1



N2



N3



N4

Conditional probability $P(F|E_i) = 1 - R(F|E_i)$

Demand	Reliability (R_9)
0	1
1	0.9990
2	0.9890
3	0.9490
4	0.8770
5	0.7100
6	0.5260
7	0.2600
8	0.0870

Demand	Reliability (R_9)
0	1
1	0.9807
2	0.9314
3	0.8158
4	0.5429
5	0.0
6	0.0
7	0.0
8	0.0

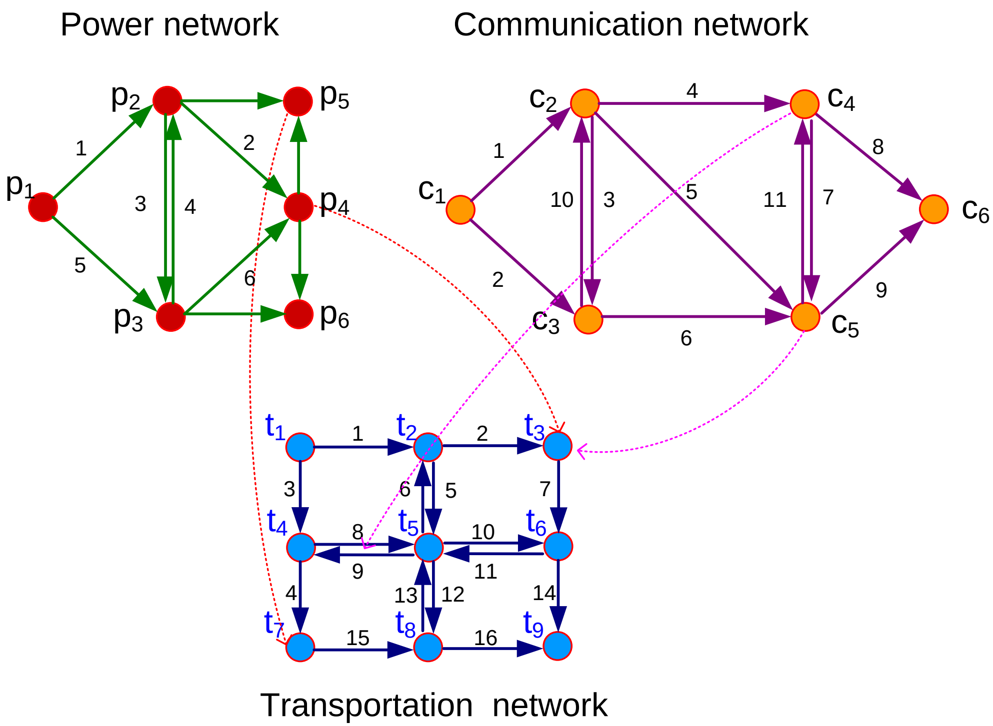
Demand	Reliability (R_9)
0	1
1	0.9799
2	0.9269
3	0.8109
4	0.6151
5	0.3743
6	0.1702
7	0.0365
8	0.0017

Demand	Reliability (R_9)
0	1
1	0.9700
2	0.8512
3	0.6589
4	0.3521
5	0.0
6	0.0
7	0.0
8	0.0

Interdependencies (*s*-independent)

$$P_{e1\cdot} = \frac{(1-R_{p_4})*6+(1-R_{p_5})*5}{6+5} = 0.5117$$

$$P_{e1\cdot} = \frac{(1-R_{c_4})*8+(1-R_{c_5})*10}{8+10} = 0.0989$$



$$P(E_1) = (1-P_{e_1})(1-P_{e_2}) = 0.4400$$

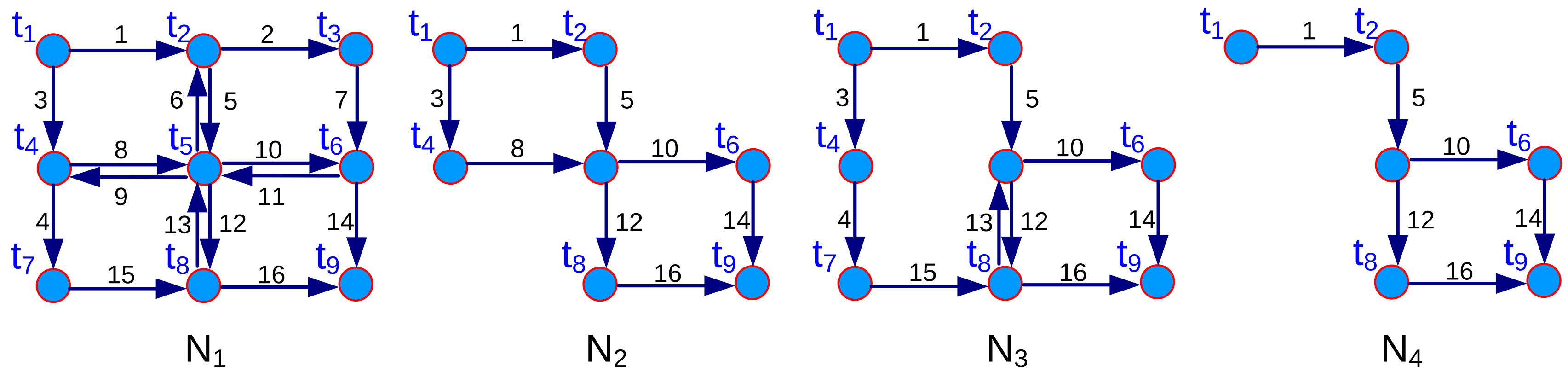
$$P(E_2) = P_{e_1}(1-P_{e_2}) = 0.4610$$

$$P(E_3) = (1-P_{e_1})P_{e_2} = 0.0482$$

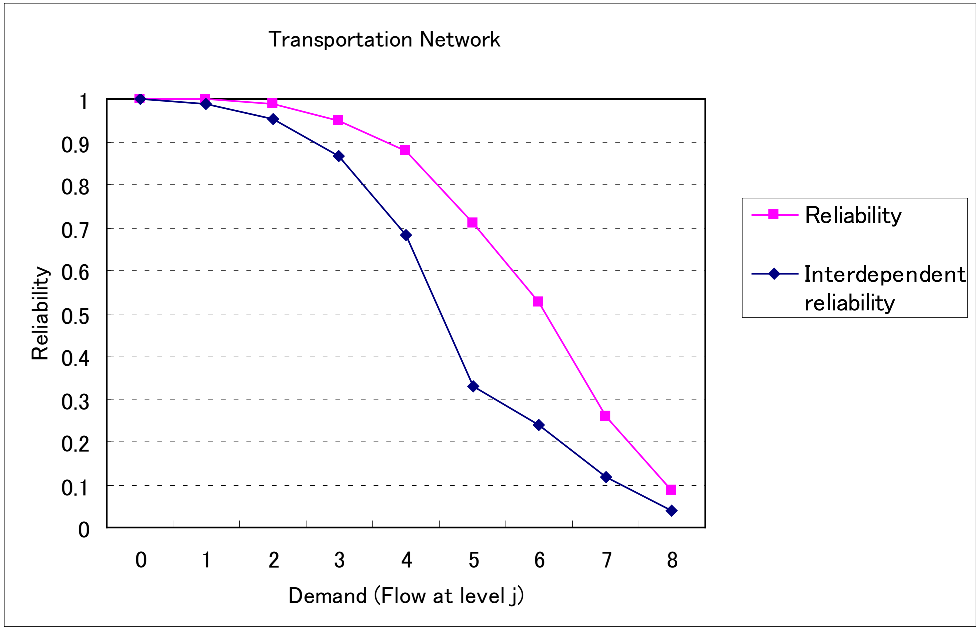
$$P(E_4) = P_{e_1}P_{e_2} = 0.0506$$

$$P_F = \sum_{i=1}^{2^m}\left[\Pr(F|E_i)\bullet\Pr(E_i)\right]$$

Multistate reliability and interdependent multistate reliability - transportation



Demand	Reliability R_9	Interdependent Reliability R_9
0	1	1
1	0.9990	0.9881
2	0.9890	0.9524
3	0.9490	0.8662
4	0.8770	0.6837
5	0.7100	0.3304
6	0.5260	0.2396
7	0.2600	0.1161
8	0.0870	0.0383



Thank you

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