MODELING OF CRITICAL INFRASTRUCTURE INTERDEPENDENCY AND INOPERABILITY PROPAGATION USING BAYESIAN NETWORKS

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CONTENTS

CIP TIMELINE OF JAPAN

1997 **IPA/ISEC** (Information-technology Promoting Agency/ Information-technology Security Center)

2000 ***Special Action Plan*** on Countermeasures to Cyber-terrorism of Critical Infrastructure

2001 **Japanese IT Security Evaluation and Certification Scheme**
National Institute of Technology and Evaluation : Ministry of Economy, Trade and Industry (METI)

First Certified Products Under Japanese IT Security Evaluation and Certification Scheme

1.Trusty Cabinet UX V1 Version 1.01 (Server Software),
Ricoh Company, Ltd.

2. INTERSTAGE Security Director 4.0,
Fujitsu Limited

CIP TIMELINE- CONTINUE

2002	Follow-up and Promotion of Measures Related to the ***Special Action Plan*** **telecom & broadcasting** – NHK and 5 keys commercial TV not to connect to external network **financial** – systems of bank and TSE to member financial institutions by dedicated lines **railroad** - dedicated traffic control and electrical power **electrical power** - basically independent from other systems **gas** - pipelines are not network nationwide and control systems of respective operators are independent from others
2003	J**PCERT/CC** (Japan Computer Emergency Response Team Coordinating Center) – in response to APCERT
2005	**NISC** (National Information Security Center)
2007	**CEPTOAR** (**Capability for Engineering of Protection, Technical Operation, Analysis and Response**)
2008	**CEPTOAR-Council**

CI INTERDEPENDENCY

- Inoperability Input-output Model
- Developed by Yacov Y.Haimes et .al

$$Normalized\ Production Loss$$

$$= \frac{\text{"}As Planned\text{"}\ Production - Degraded\ Production}{Normalized\ Production}$$

- $\mathbf{q} = \mathbf{A^*q} + \mathbf{c^*} = (\mathbf{I} - \mathbf{A^*})^{-1}\mathbf{c^*}$
- **q** is the inoperability vector expressed in terms of normalized economic loss. The elements of **q** represent the ratio of unrealized production
- **A*** is the interdependency matrix which indicates the degree of coupling of the industry sectors.
- **c*** is a demand-side perturbation vector expressed in terms of normalized degraded final demand

Reference: Joost R.Santos and Yacov Y.Haimes, Modeling the Demand Reduction Input-output Inoperability Due to Terrorism of Interconnected Infrastructures, Risk Analysis, Vol. 24, No.6, 2004

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LIMITATIONS

- Logical or economic interdependency ***(not functional)***
- Leontief Economic Model which requires ***certain duration for maintaining equilibrium state***
- Most of CI are ***utility systems*** which represent ***low economic value in Input-Output tables***

MODEL OVERVIEW

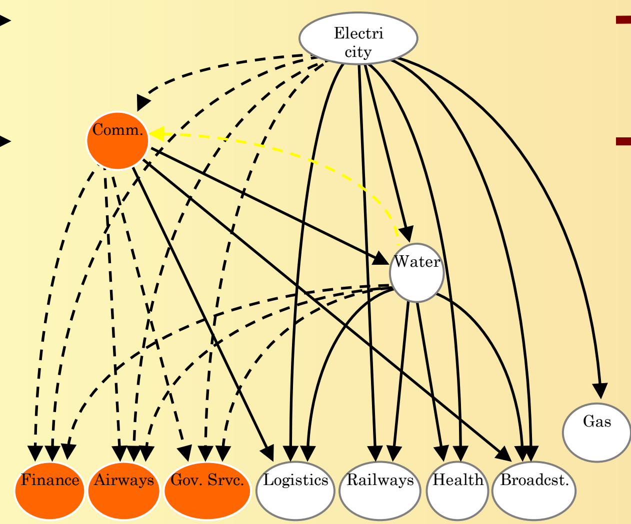
External Perturbation at Finance system

External Perturbation at Electric system

External Perturbation at Communication system

Bayesian Network for selected CI constructed upon domain expert knowledge

<No other cascading effect>



Same Perturbation at Finance system

Perturbation at Electric system and Secondary impact at other 10 systems

Perturbation at Communication system and Secondary impact at other 6 systems

Perturbation input for IIM

DATA SOURCES

- NILIM Report (2009)
  - Conducted by **National Institute of Land and Infrastructure Management (NILIM)**
  - Include 5 major parts:
    - review on 65 governmental reports on Kobe earthquake and 52 reports on Niigata Chuetsu earthquake
    - Interview with Government officials and CI sector companies
    - Questionnaire Survey
    - Influence matrix formulation
    - Case study on simulated Tokyo Metro Area earthquake
  - Focus on physical & operational dependency
- NISC CI Interdependency Study reports (2007-2009)
  - Focus on functional and information dependency of Japan CI

NILIM REPORT (2009)

- **“Model development of interdependency among critical infrastructures and simulation of earthquake damage spreading”**
- review on 65 governmental reports on Kobe earthquake and 52 reports on Niigata Chuetsu earthquake and,
- Unique 244 CI-to-CI dependencies and 77 CI-to-CI dependencies are identified and categorized into six categories

    1. physical impact (18 cases)
    2. functional impact (33 cases)
    3. restoration delay (62 cases)
    4. alternative impact (43 cases)
    5. common failure (4 cases)
    6. lifeline impact (84 cases)

SOME SNIPPETS FROM REPORT

No.	Influence generated	Influence received	Type	Detail
1.	Water Supply	Health	lifeline	8850m^3 volume of water required to transport by trucks (47 days starting from Jan 21)
16.	Road	Water Supply	Restoration	Only 66.5% of employee can reach work place at the day of disaster due to traffic congestion
30	Water Supply	Road	alternative	Water requirement increase from 5-6 ton to 30 ton for hospital operation and need to transport water using tank truck from places as far as 7km
32	electricity	Health	lifeline	Inoperability of artificial respirator threaten 16 lives and staff and families volunteer to operate the artificial respiration with hand pressure
95	Water	Gas	Physical	Gas supply halt in 12,463 places due to water leakage into control apparatus
104	Comm.	Industry	lifeline	The one of two trunk lines (NTT Online cable) was broken between Computer Center and Kobe head office
13	Road	Gas	Restoration	Due to serious road damages in valley, Gas workers cannot get access to Yamaguchi and Horikoe region for 3 days
25	gas	Waste disposal	functional	Sewage is being use in cooling of pressured gas
16	Comm.	gas	Restoration	Delay occur in SCADA data arrival at Nagaoka Control Center and it took 2 hour delay to reach Kawaguchi gas control unit

QUESTIONNAIRE RESULTS (FUNCTIONAL DEPENDENCY)

CI / Lifeline

		終点（インフラ）									終点（社会的機能）			
		電力	ガス	上水道	下水道	情報通信	道路	鉄道	港湾	航空	運輸・物流/旅客	金融	医療	行政
起点	電力		1	3	8	4	9	16	12	8	12	8	12	16
	ガス	1		1	2	1	0	4	1	3	1	1	6	2
	上水道	2	1		4	0	0	4	3	3	4	1	16	8
	下水道	0	0	1		0	0	4	1	1	1	1	4	1
	情報通信	0	8	2	1	(3)	4	16	4	8	12	20	6	20
	道路	0	4	2	0	12	(12)	1	8	4	16	6	12	2
	鉄道	0	1	0	0	0	6	(3)	3	4	4	2	0	2
	港湾	0	3	0	0	0	0	0		0	1	0	0	12
	航空	0	0	0	0	0	0	0	0		1	0	0	0

凡例

評価値	セル色
1～2	レベル1
3～4	レベル2
5～6	レベル3
7～10	レベル4
11～20	レベル5

K^{TH} ORDER IMPACT (NILIM STUDY)

- $\{y_1\} = \{x\} [C]$
- $$\{y_k\} = \sum_{j=1}^{k} \{x\}[C]^j$$
- *Where;*
  - $\{y_k\}$ = compounded impact generated by k^{th} order
  - $\{x\}$ = row vector of impact in 'n' sector
  - [C] = interdependency matrix of 'n x n' order

SETTING (4) : INFLUENCE MATRIX

- Setting (4)
- Assessment level – from 0 to 20
- Normalized base on the highest value (= 61) of row-wise summation
  (*notes: lifeline impact are omitted*)

	Electricity	Gas	Water	Sewage	Comm	Road	Railway	Harbors	Air
Electricity	0	0.016393	0.04918	0.131148	0.065574	0.147541	0.262295	0.196721	0.131148
Gas	0.016393	0	0.016393	0.032787	0.016393	0	0.065574	0.016393	0.04918
Water	0.032787	0.016393	0	0.065574	0	0	0.065574	0.04918	0.04918
Sewage	0	0	0.016393	0	0	0	0.065574	0.016393	0.016393
Comm	0	0.131148	0.032787	0.016393	0	0.06557	0.262295	0.065574	0.131148
Road	0	0.065574	0.032787	0	0.196721	0	0.016393	0.131148	0.065574
Railway	0	0.016393	0	0	0	0.098361	0	0.04918	0.065574
Harbors	0	0.04918	0	0	0	0	0	0	0
Air	0	0	0	0	0	0	0	0	0

TOTAL IMPACT (DIRECT + INDIRECT)

- DEMATEL method
- $[F] = [C]\ [I\text{-}C]^{-1}$
- Where;
  - [C] = setting (4) interdependency matrix
  - [F] = Total impact (direct + indirect)

D = Influence **D**riving (sum of a row's elements)
R = Influence **R**eceiving (sum of a column elements)

	Electricity	Gas	Water	Sewage	Comm	Road	Railway	Harbors	Air
Electricity	0.003027	0.060529	0.062064	0.139291	0.103214	0.185284	0.310372	0.249977	0.185895
Gas	0.017125	0.006658	0.018984	0.036822	0.019919	0.01166	0.079578	0.028158	0.061886
Water	0.033289	0.023033	0.003787	0.071028	0.005186	0.013347	0.082301	0.063595	0.062982
Sewage	0.0006	0.003098	0.016766	0.001303	0.001434	0.006833	0.067607	0.021723	0.02254
Comm	0.003768	0.150483	0.039683	0.024776	0.021507	0.095532	0.284585	0.099075	0.169147
Road	0.003076	0.103339	0.042159	0.009882	0.20289	0.021722	0.080962	0.155817	0.106637
Railway	0.000625	0.029102	0.004504	0.001665	0.020331	0.100717	0.009461	0.065036	0.077227
Harbors	0.000842	0.049508	0.000943	0.001811	0.00098	0.000573	0.003914	0.001385	0.003044
Air	0	0	0	0	0	0	0	0	0

INDUSTRY BY INDUSTRY TOTAL REQUIREMENT TABLE FOR JAPAN

Source: Japan 2000 Input-output table

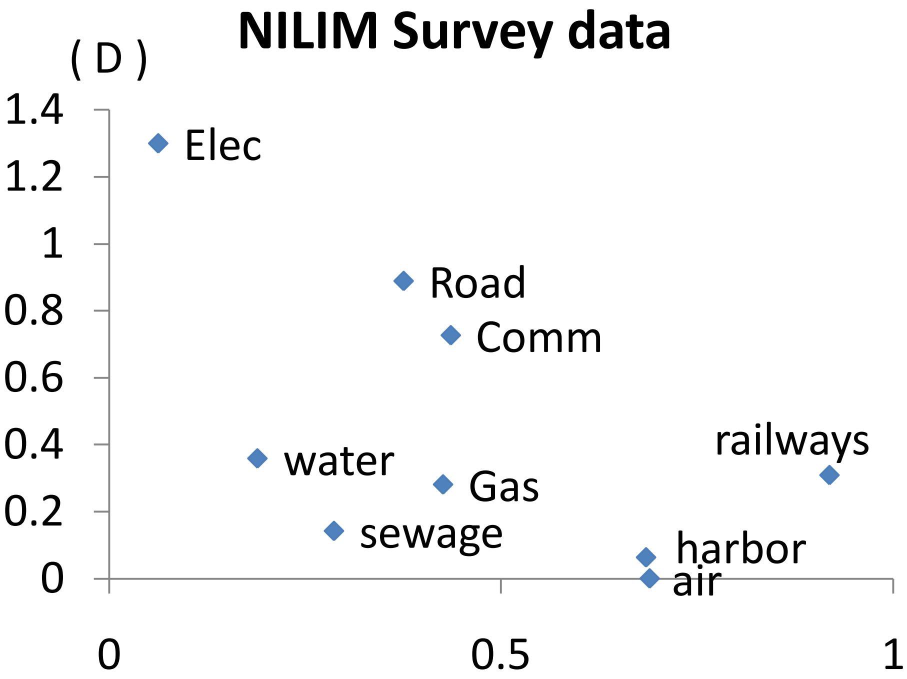
{ I-(I-M)A}^-1 (Competing Import model)

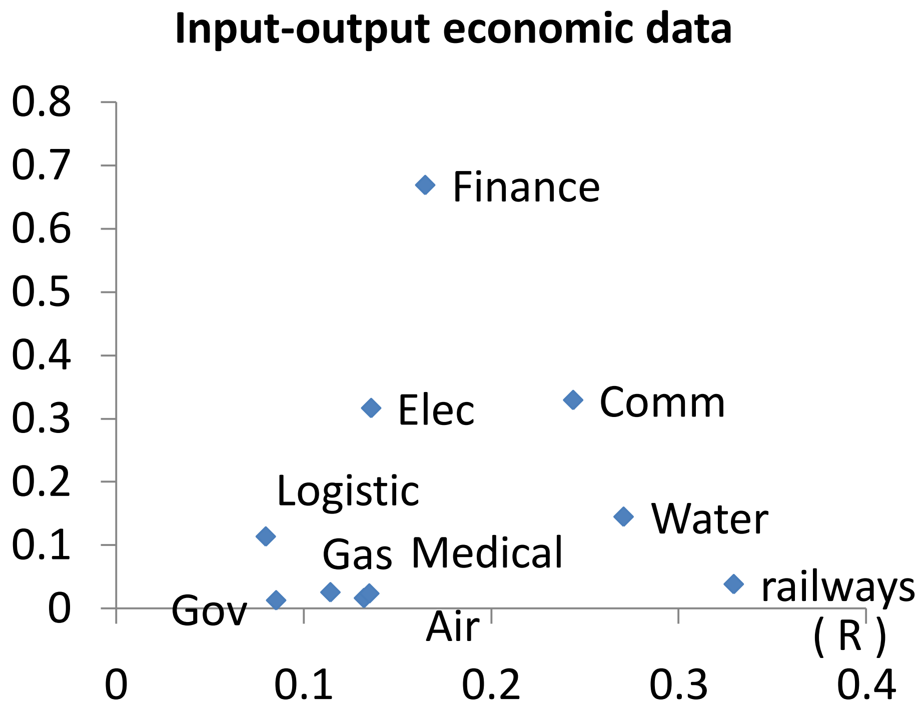
	ELEC.	GAS	WATER	FINC	RAIL	LGSTC	AIR	COMM	GOV	MED
ELEC.	1.043578	0.025498	0.093584	0.0082	0.060693	0.011241	0.015587	0.015551	0.017824	0.02493
GAS	0.000534	1.012813	0.001717	0.001005	0.001095	0.000808	0.001316	0.001071	0.001191	0.003883
WATER	0.001937	0.005211	1.105431	0.002248	0.006977	0.002976	0.003473	0.004135	0.004786	0.007713
FINANCE	0.059927	0.029559	0.034154	1.099556	0.232122	0.038274	0.071628	0.046012	0.020523	0.037563
RAIL	0.002233	0.002142	0.00242	0.009354	1.003249	0.002407	0.002884	0.002962	0.006447	0.004207
LOGISTIC	0.012923	0.020586	0.011587	0.008528	0.006226	1.006349	0.007863	0.015381	0.010985	0.013164
AIR	0.000791	0.00063	0.000836	0.001372	0.000626	0.000505	1.005925	0.002804	0.001273	0.001525
COMM	0.012735	0.016381	0.018865	0.032934	0.017441	0.015884	0.021257	1.154597	0.021695	0.017611
GOV	0.00123	0.00131	0.001932	0.001498	0.000911	0.001205	0.002105	0.001109	1.00044	0.000994
MEDICAL	0.000007	0.000024	0.000054	0.000034	0.00003	0.000004	0.000006	0.000049	0.000014	1.0233

Industry by industry total requirements table, used to calculate total industry requirements for a dollar of industry output.

INFLUENCE DRIVING (D) & INFLUENCE RECEIVING (R)

D = Influence driving (sum of a row's elements)
R = Influence receiving (sum of a column elements)





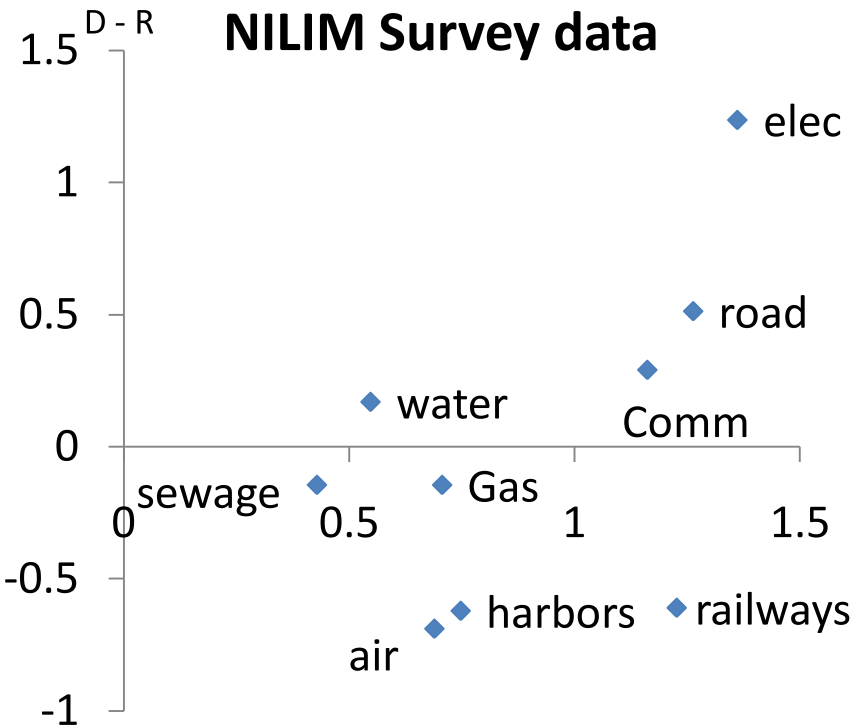
X-axis = Influence receiving (R)
Y-axis = Influence driving (D)

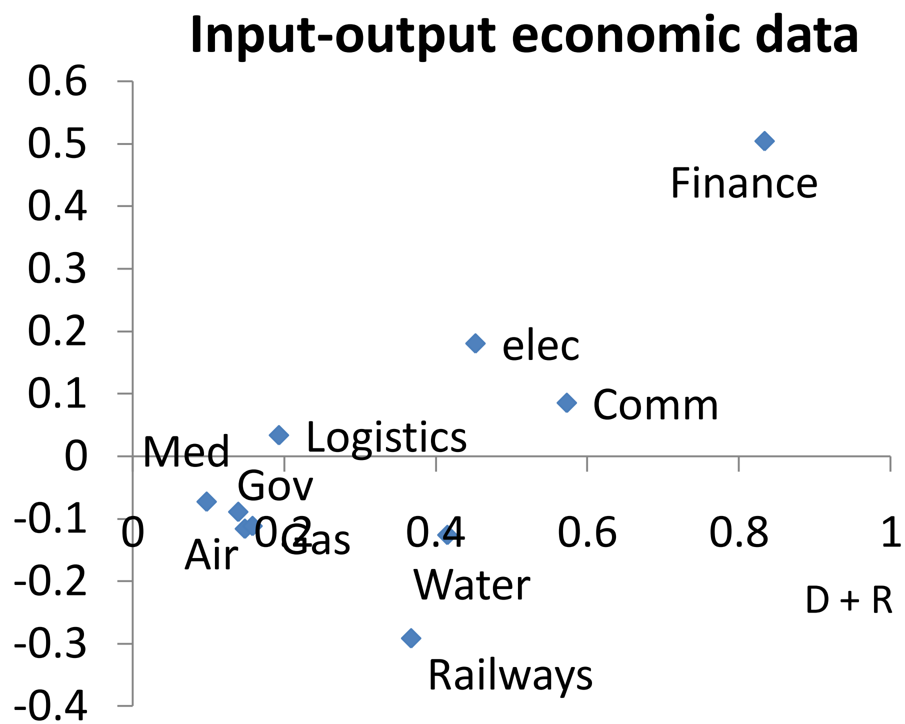
STRENGTH OF RELATION & NET INFLUENCE

D+R = strength of relation with other CI

D-R = net influence ; if (D-R) is positive (+) --> net influence driving CI

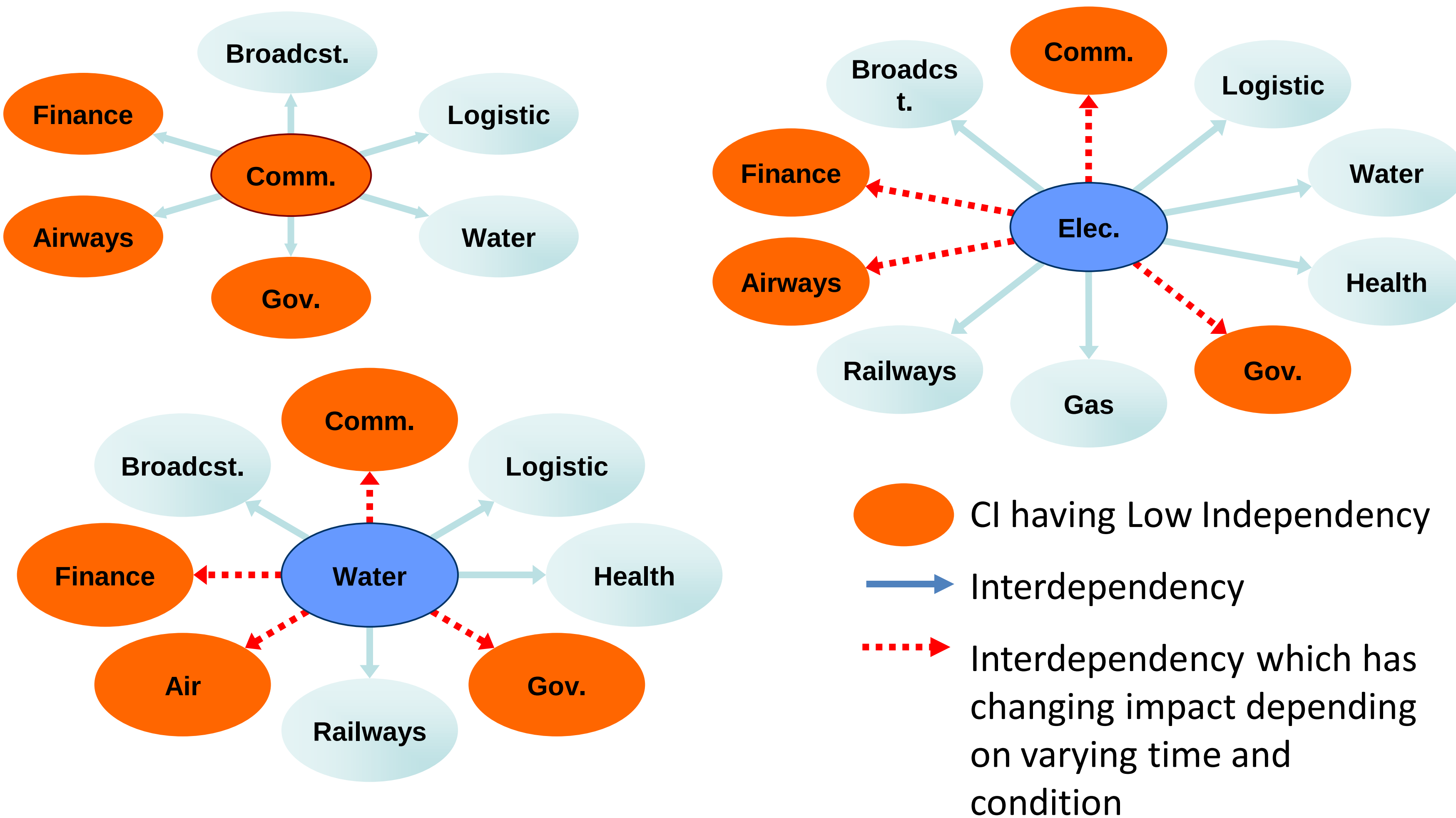
if negative (-) --> net influence receiving CI





X-axis = strength of relation (D +R) Y-axis = net influence (D-R)

NISC SURVEY REPORT SUMMARY



Remark: Communication and Broadcasting are separated making 11 CIs

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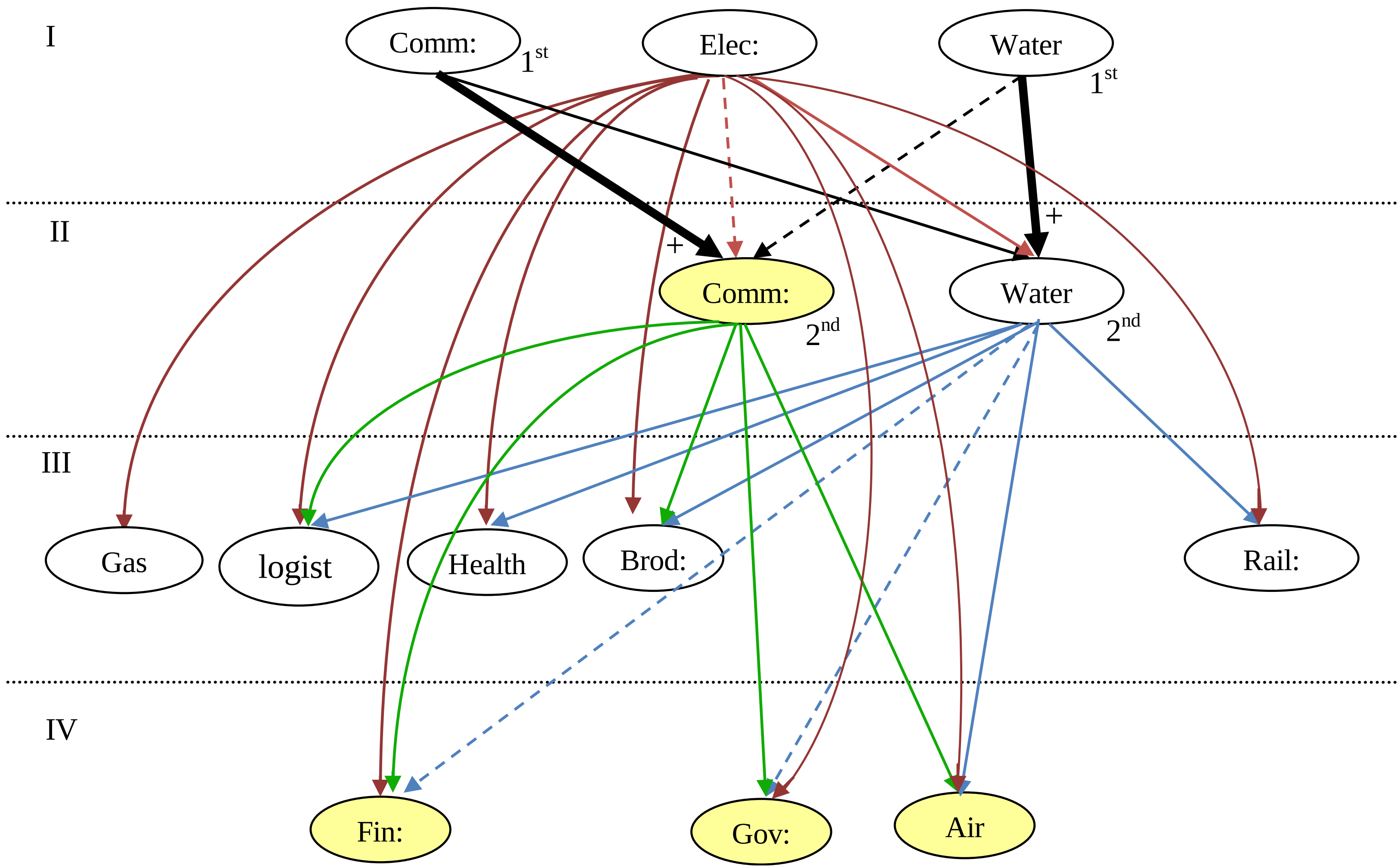
CAUSAL NETWORK



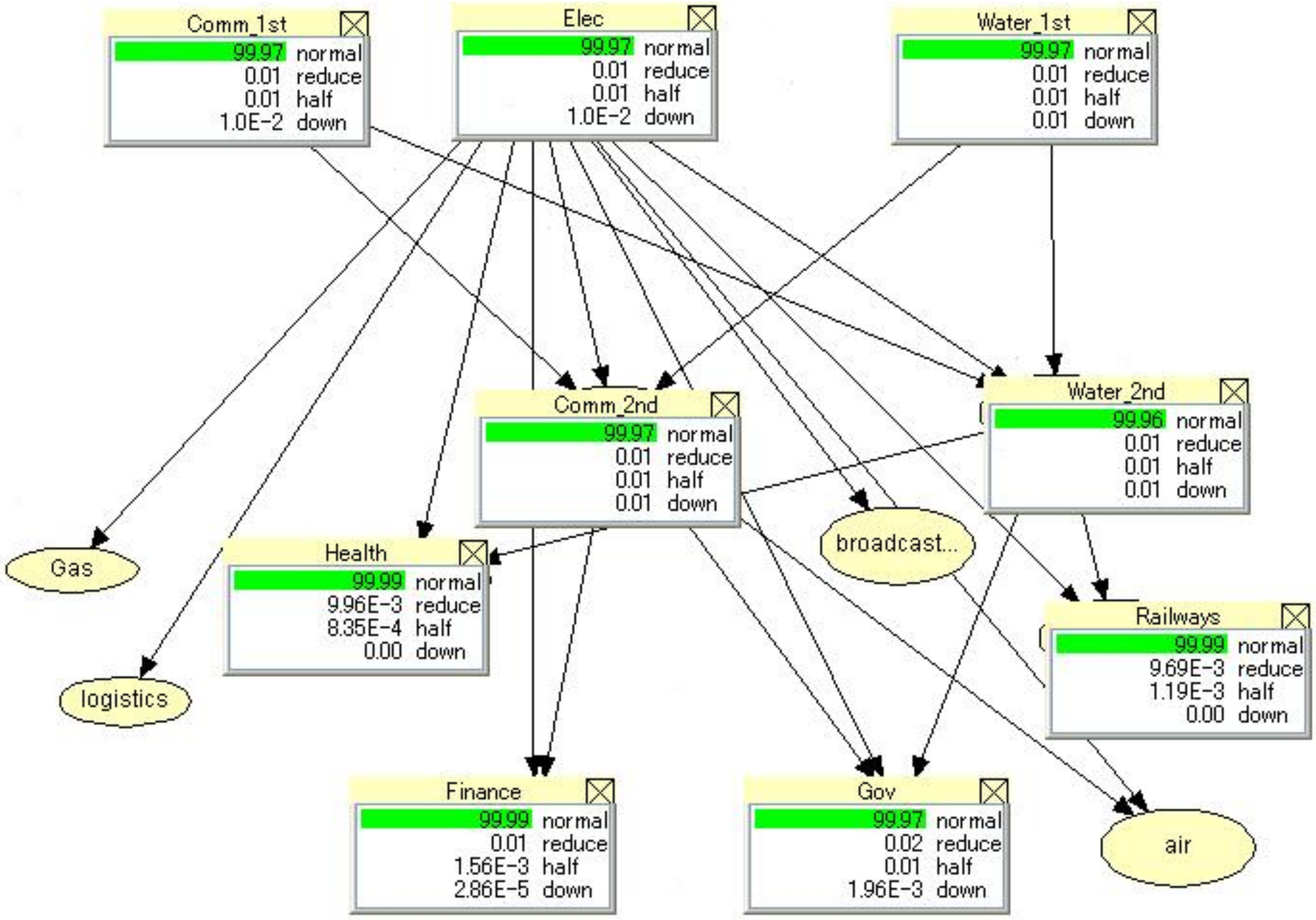
BAYESIAN PROBABILISTIC NETWORK CONSTRUCTION

- Mainly target on functional dependency
- It is modeled for *one-day* period
- Network structure is taken from NISC survey result
- Influence level (conditional probability) are driven from NILIM questionnaire results and matrix formulation of setting (4)
- Qualitative judgment is done based on:
  - The reasons and rating written in questionnaires by participants
  - Functional impact cases from data-mining of previous disasters
  - Interview notes
  - NISC survey results – such as direct or time variant impact, CI independency and reasons behind of these results

STATES OF DECISION NODES

- **Normal** = the system is in normal condition, fully operating, inoperability (0.00)
- **Reduced** = the system is slightly perturbed, only 80% is functioning, inoperability (0.20)
- **Half** = half of the system is out of operation, inoperabiilty (0.50)
- **Down** = the system is down, completely out of service, inoperability (1.00)

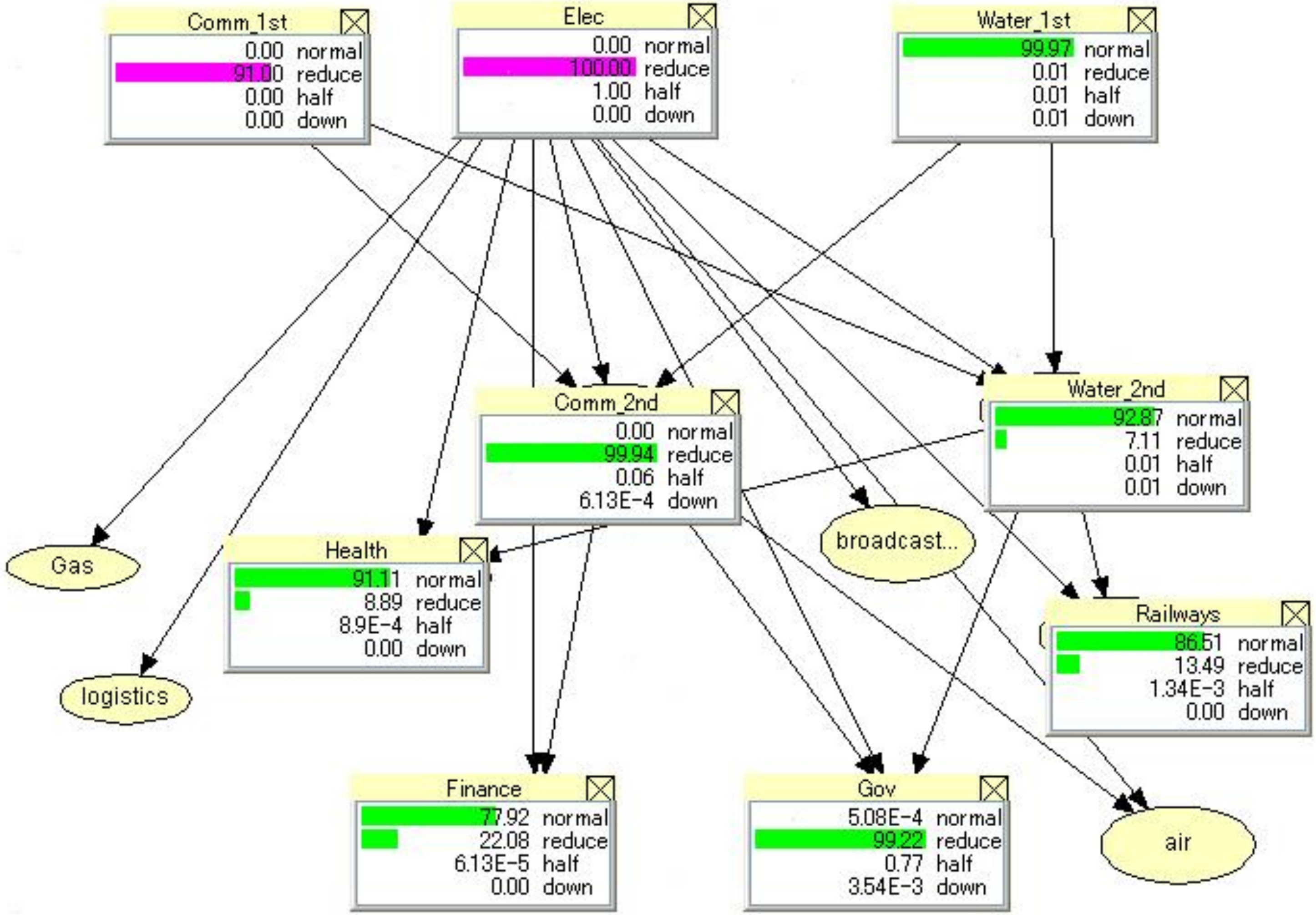
BAYESIAN NETWORK INITIAL SETTING



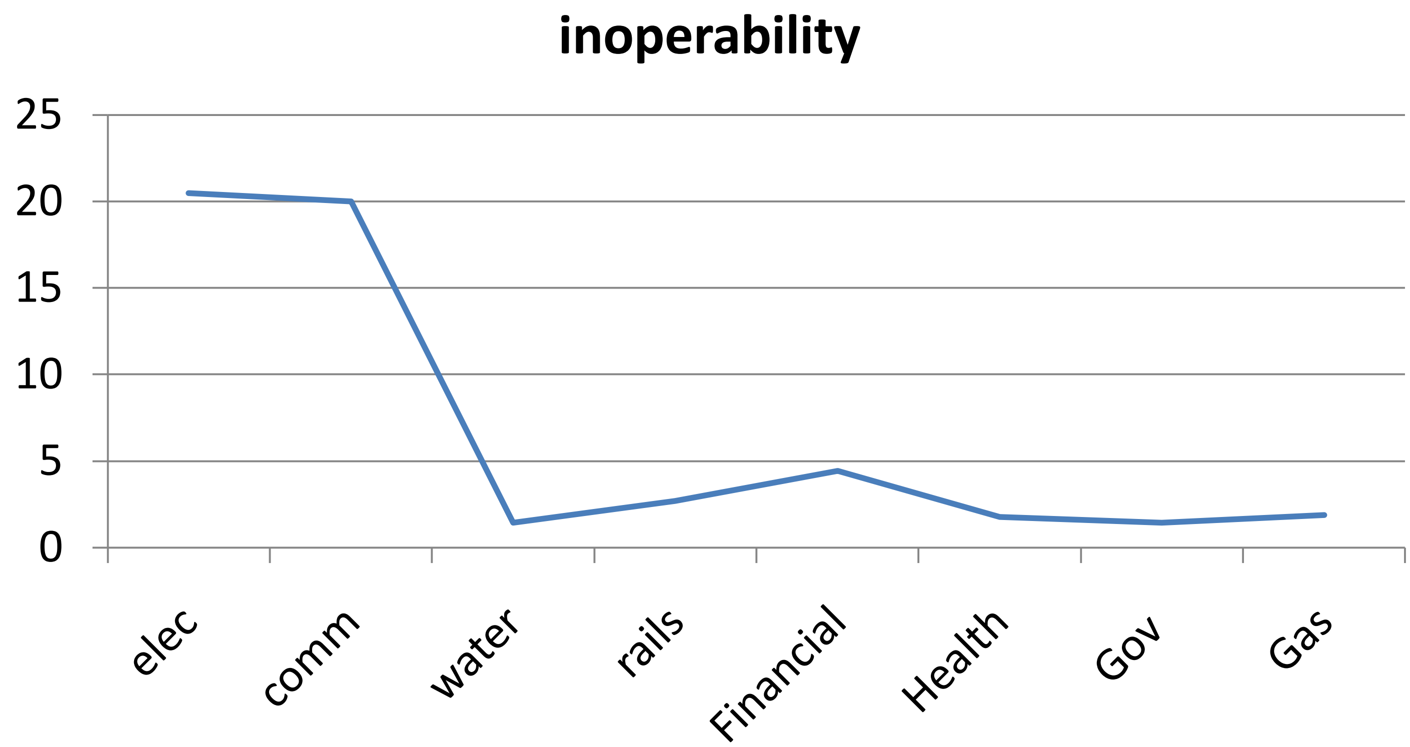
CASE STUDY

- Earthquake damage estimates are taken from
  Disaster assessment relating to Tokyo Metro Area earthquake, 2006
  Published by **Japanese Government Earthquake Management Center**
- Study Area : Around **Shinagawa Area**
- Predicted Magnitude scale : **7.2 M**
- Potential Electricity service disruption: 20.5%
- Potential Communication service disruption: 18.2%

INOPERABILITY PROPAGATION



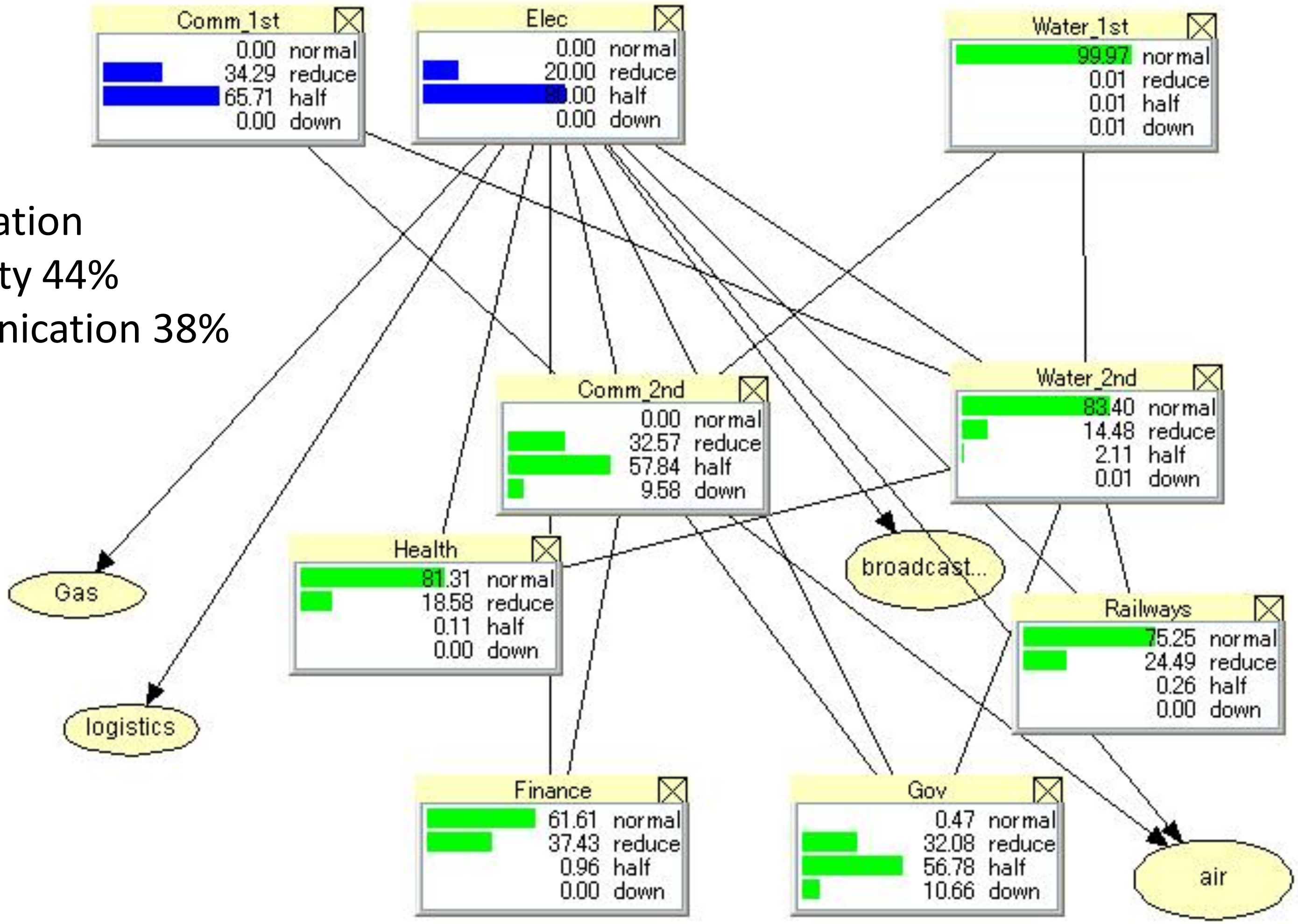
PROPAGATED INOPERABILITY DUE TO SERVICE DISRUPTION IN ELECTRICITY & COMMUNICATION



Inoperability due to 6.9 M earthquake in Tokyo Shinagawa area.

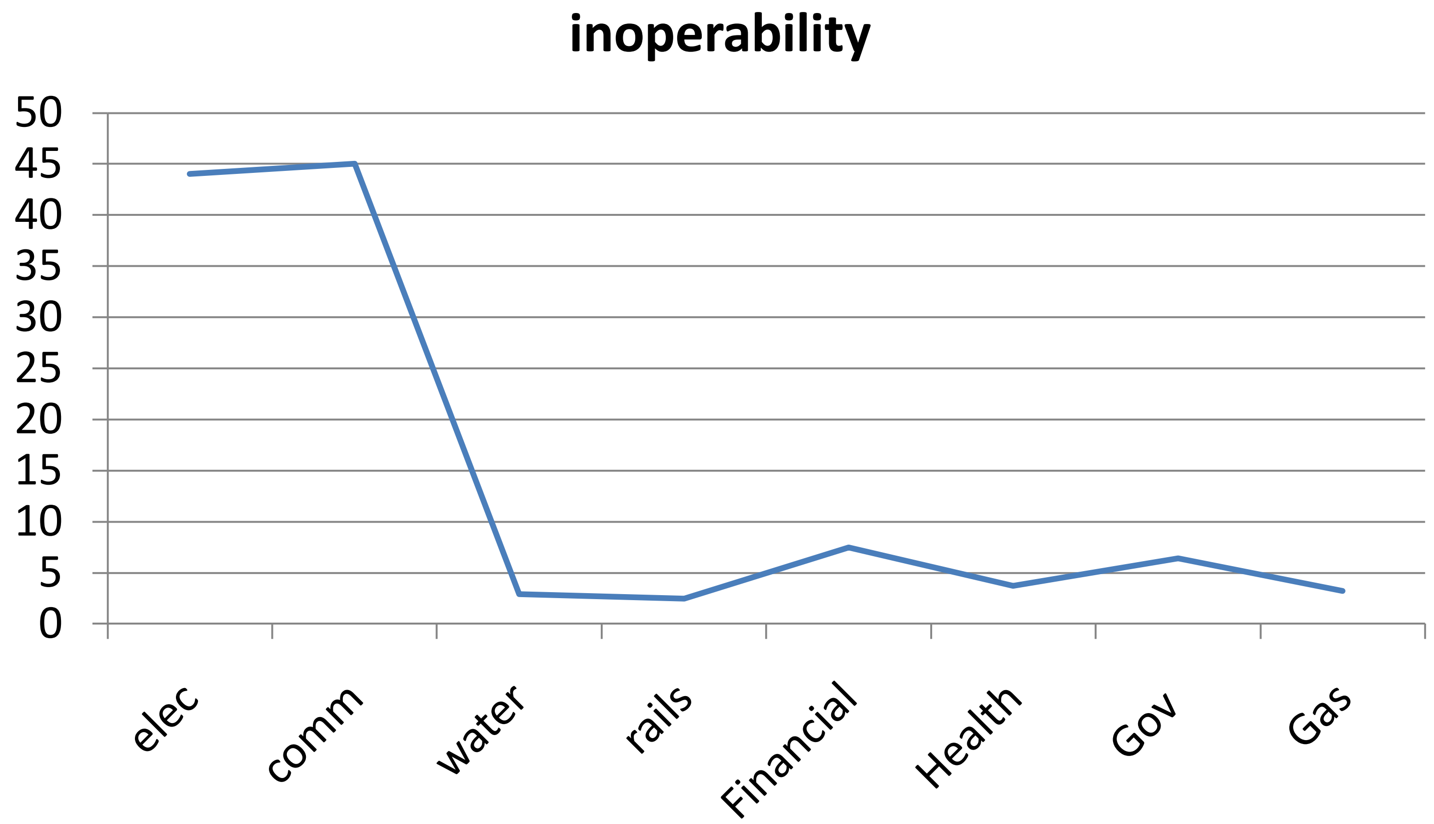
USING MAXIMUM DISRUPTION ESTIMATE

Perturbation
Electricity 44%
Communication 38%



Inoperability due to 7.3 M earthquake in Tokyo Shinagawa area. (Using maximum value)

PROPAGATED INOPERABILITY DUE TO SERVICE DISRUPTION IN ELECTRICITY & COMMUNICATION (MAX)



FUTURE WORK

- Conditional probability setting should be refined using specific questionnaires to stakeholders
- Validation with post disasters for model accuracy

QUESTIONS & ANSWERS

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Information System Risk Management Laboratory

Thank You

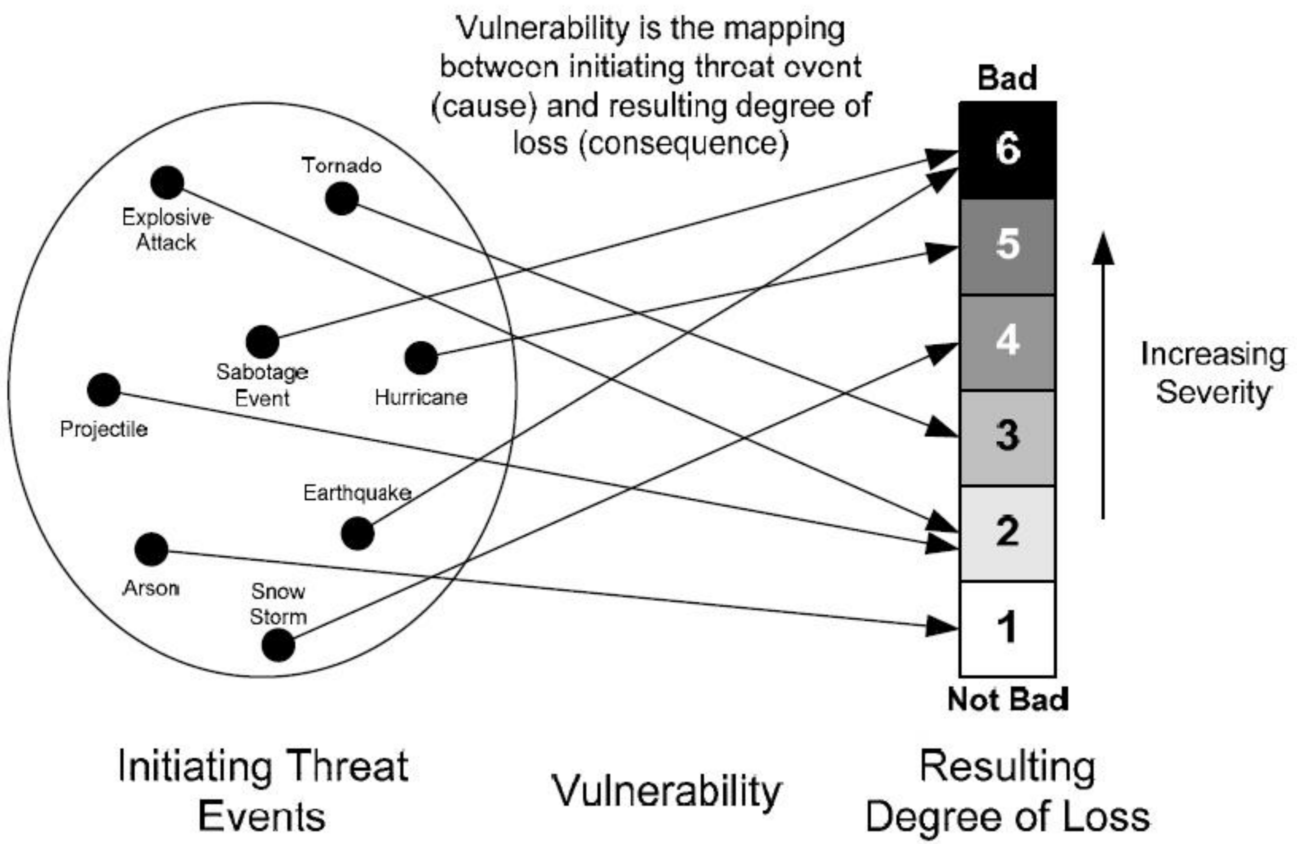
THIRD DIMENSION FOR RISK ASSESSMENT

- Risk = Threat × Vulnerability × Consequence
  Source: W. McGill and B. Ayyub,
  The meaning of vulnerability in the context of critical infrastructure protection
- Risk = Probability × Complexity × Severity
  Source: Z. Aung, Operational Risk Management Framework for Service Outsourcing: -Consideration of Risk Dimensions and Their Application to the Framework-
- Risk = Probability × Consequence × Uncertainties
  Source: T. Aven, Identification of safety and security critical systems and activities
- Risk = Probability × Severity × Time
  Source: K. Masaoka, Proposed risk assessment model incorporating the concept of time

(Remark: Symbol “ × ” not necessarily means multiplication.)

VULNERABILITY AS A MAPPING

W. McGill and B. Ayyub



COMPLEXITY AS A THIRD DIMENSION

✓- The level of complexity in detecting threat (monitoring)
✓- The level of complexity in measuring the consequence (uncertainty)
✓- The level of complexity in prevention (vulnerability)

Probability
- Likelihood of Risk Occurrence

Complexity
- Interdependency
- Degree of difficulty for detecting, measuring and preventing
- Limited time allowance for reactive action

Severity
- Amount and duration of impact
- Time to recover

UNCERTAINTY IN RISK ASSESSMENT

- **Terje Aven**: *"identification of safety and security critical systems and activities".*
- risk is more than expected values and uncertainties need to be taken into account.
- Probability is not a perfect tool for expressing uncertainties.
- Probabilities are based on background information that may hide a number of assumptions and suppositions, and *these assumptions and suppositions can be wrong.*
- Suggested an approach which combines expected value assignment and assessment of uncertainties in underlying phenomena and processes.

INCORPORATING THE CONCEPT OF TIME

- **K. Masaoka**, *"Proposed risk assessment model incorporating the concept of time"*
- a risk assessment model which quantify risk and determine priority based on time element.
- the environment which surrounds any actual phenomenon is changing at every moment and;
- it reflects on the occurrence probability of incidents, the impact and urgency as well.