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A general framework for critical infrastructure interdependencies modeling using economic input-output model and network analysis

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Critical infrastructure interdependency

What is Critical infrastructure?

Infrastructure (industries) that provides a continuous flow of goods and services essential for the functioning of a society and economy (Clinton 1996)

What is infrastructure interdependency?

A bidirectional relationship between two infrastructures in which the state of each infrastructure influences or is correlated to the state of the other infrastructure. (Rinaldi et al. 2001)

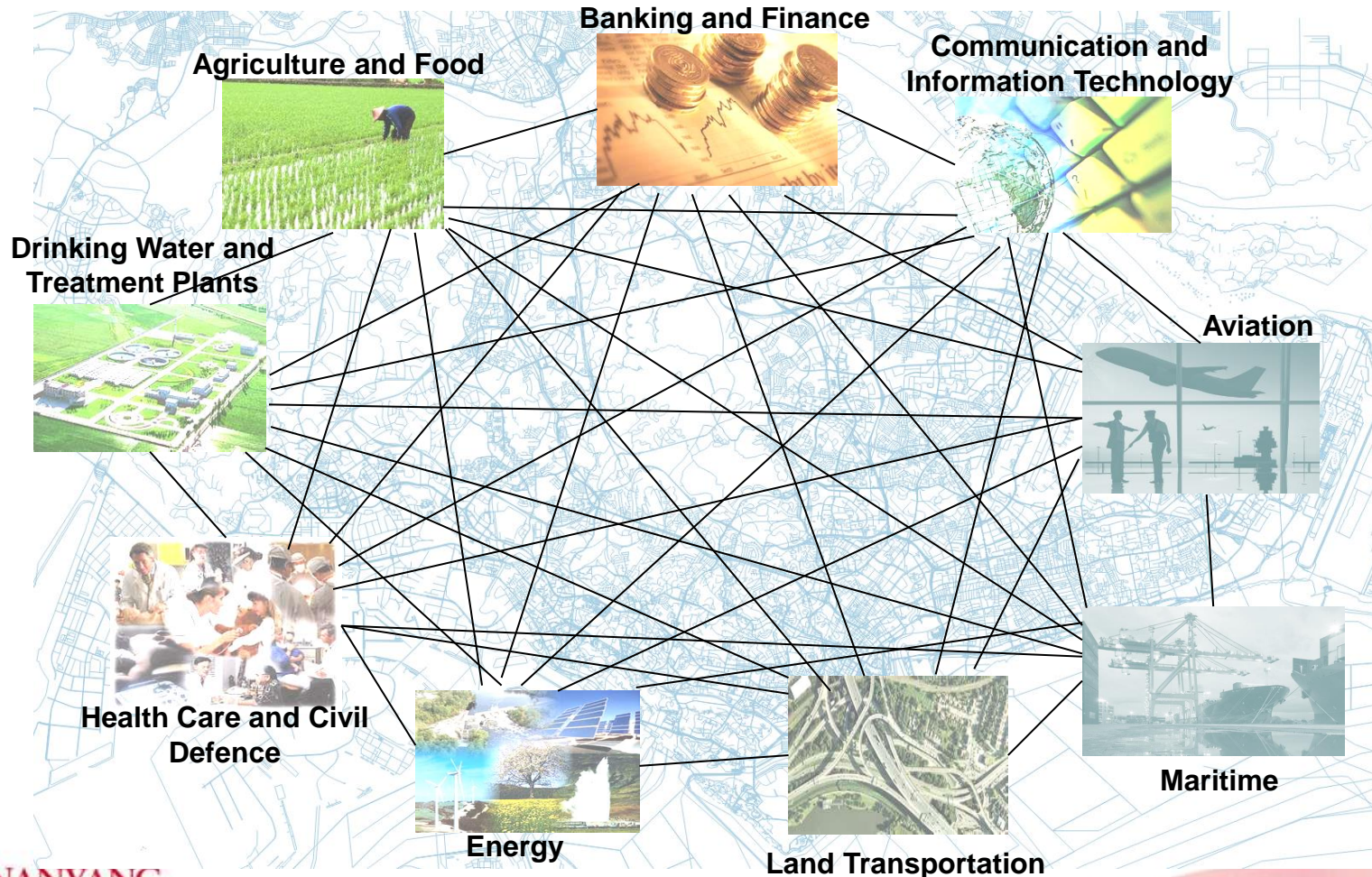
Clinton, W.J. (1996) "Executive order 13010 - Critical infrastructure protection", Federal Register, Vol.61, No.138, pp.37347-37350

Rinaldi, S.M.; Peerenboom, J.P.; Kelly, T.K., 2001) "Identifying, understanding, and analyzing critical infrastructure interdependencies," in *Control Systems, IEEE*, vol.21, no.6, pp.11-25

Critical infrastructure analysed in this study



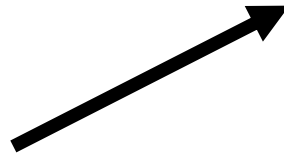
Critical infrastructure are interconnected



Example of the interconnected nature of critical infrastructure



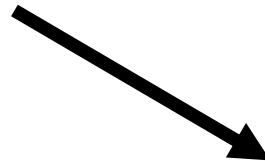
9/11 terrorist attacks



Banking and Finance



Transportation Infrastructures



Commercial and Industry

Observation from the example

- Disturbances (or hazards) can affect two or more infrastructures
- They are the consequences of the **interaction between different infrastructures**, due to their interconnected nature
- These interactions reflect the **interdependencies**.

Issues in establishing network relationship (interdependence)

- Difficulty in accessing the data
 - Modeling requires relevant data such as the interdependencies between multiple CI sectors
 - Even if there is expert knowledge
 - There may still be some unforeseen interdependencies between the CI sectors
- No standardized way of data collection
 - Different methodologies have different definitions on critical infrastructure and their interdependencies
- In order to link all critical infrastructure together, a common metric or denomination may be required
 - In our case, using monetary value

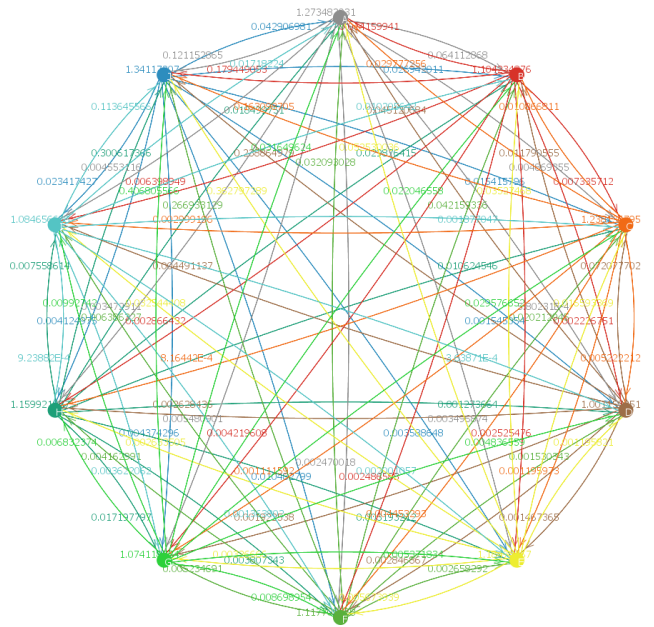
Key Research Issues in critical infrastructure interdependency analysis

- What is the network relationship (interdependence) between critical infrastructures?
- To improve the understanding of any impact that propagates within a critical infrastructure network system
- To analyse and simulate the worst case scenario

I/O interdependency model

Aggregated from the original 136 sector I/O table

sales by industry \ sales by commodity	Banking and Finance	Information- and Telecommunications	Electricity	Water	Transportation	Health	Food supply	Aviation Security	Maritime Security	Others	Total final output	TOTAL OUTPUT
Banking and Finance	11,695.3	141.6	130.4	29.7	164.8	152.0	176.6	106.8	370.7	12,683.4	29,552.9	55,204.7
Information- and Telecommunications	2,427.3	2,237.0	38.8	4.5	121.7	273.1	144.2	349.5	229.5	8,463.8	10,317.7	24,607.4
Electricity	104.8	90.1	1,611.2	58.6	50.9	114.7	251.3	88.5	11.0	4,618.0	1,446.3	8,445.5
Water	12.6	44.2	34.2	0.6	3.4	9.0	53.9	13.1	7.0	536.3	333.1	1,048.1
Transportation	111.2	37.7	3.9	0.6	959.0	12.8	45.0	31.7	48.7	1,094.5	3,839.2	6,184.5
Health	55.3	20.7	19.2	0.7	12.7	980.3	61.8	19.7	13.6	3,578.2	4,706.9	9,468.7
Food supply	195.6	74.0	2.8	0.9	8.4	32.4	926.1	250.0	103.9	1,423.0	0	13,690.9
Aviation Security	110.2	43.7	1.3	1.6	6.0	23.3	60.3	7	15.4	1,300.2	8	19,317.3
Maritime Security	87.1	65.9	0.4	0.2	125.7	11.9	31.1	32.8	8	8,267.8	8	38,159.4
Others	3,458.1	4	802.0	175.2	5	1	8	8	2	2.0	8.4	9
VALUE ADDED AT BASIC VALUES	28,913.2	8,016.9	2,314.8	540.7	3,129.6	5,029.1	4,237.6	6,160.5	9,874.4	183.85	0.0	252,074.2
TOTAL INPUT	55,204.7	4	8,445.5	1,048.1	6,184.5	9,468.7	13,690.9	19,317.3	38,159.4	518,46	534,70	1,229,29



I/O interdependency network model



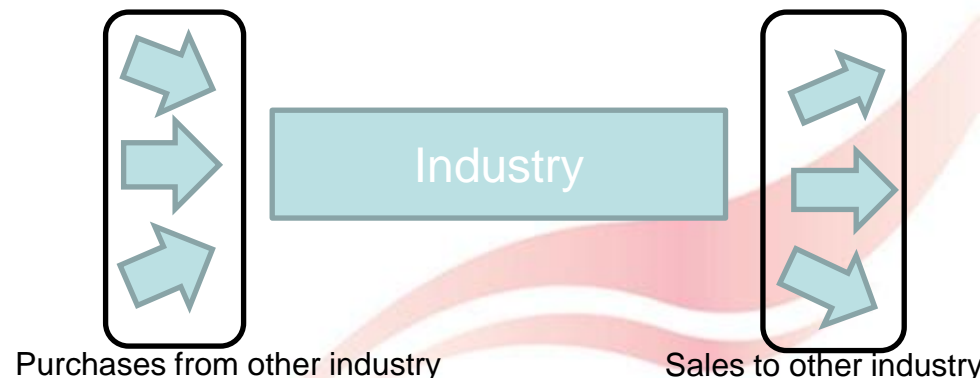
Choosing the approaches

Type of approaches	Quantity of input data	Accessibility of input data	No of types of interdependencies possible in the model	Maturity of approaches
Empirical based	Medium to High	Medium to High	Low	Medium
Simulation based	High	High	High	High
Input-output based	Medium	Low to Medium	Low	Medium to High
Network based	Low to Medium	Low to Medium	Low	High
Others (includes HHM and “supernetwork”)	High	Medium to High	Medium	Low

Input-output & Network Based approach have been selected

Advantages of Input-Output model as critical infrastructure model

- Advantages
 - Accessible and suitable data available in public domain
 - I/O model is fundamentally linear in nature
 - Rapid computation
 - Flexibility in computing the effects of changes in demand.
 - Good representation of the inter-industry transaction which represents the interdependencies between all industry sectors in a nation .(Thijs Ten Raa, 2009)

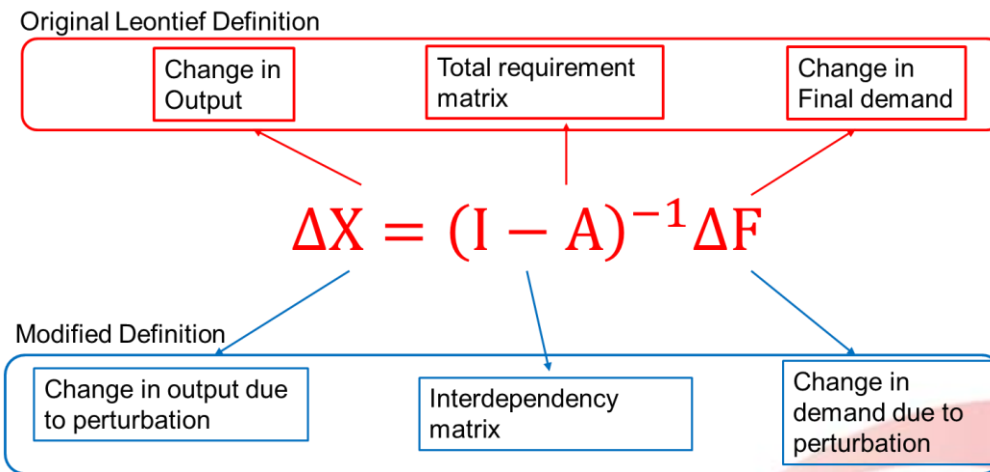


I/O model as critical infrastructure model

- Depicts inter-industry relationships within an economy, showing how output from one industrial sector may become an input to another industrial sector.
 - Enables a way to analyze the economy as an interconnected system of industries
 - Enables estimation of economic impacts of any change to economy based on inter-industry transaction
- Demand-pull input-output quantity model (Miller & Blair, 2009)

$$X_i = \sum Z_{ij} + f_i$$

- X_i = Total output of goods and service produced by sector i
- Z_{ij} = Inter-industry transactions
- f_i = Final demand



Direct effect, indirect effect and total impact



Total impact ΔX (sum of all sector's change in output due to perturbation)

Direct ΔF



I/O interdependency matrix

Indirect



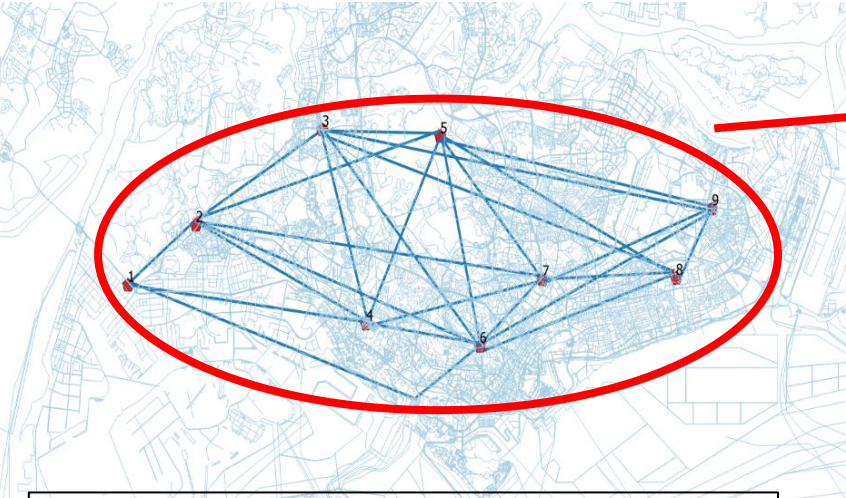
$$\Delta X = (I - A)^{-1} \Delta F$$

Disadvantage of I/O model for critical infrastructure modeling

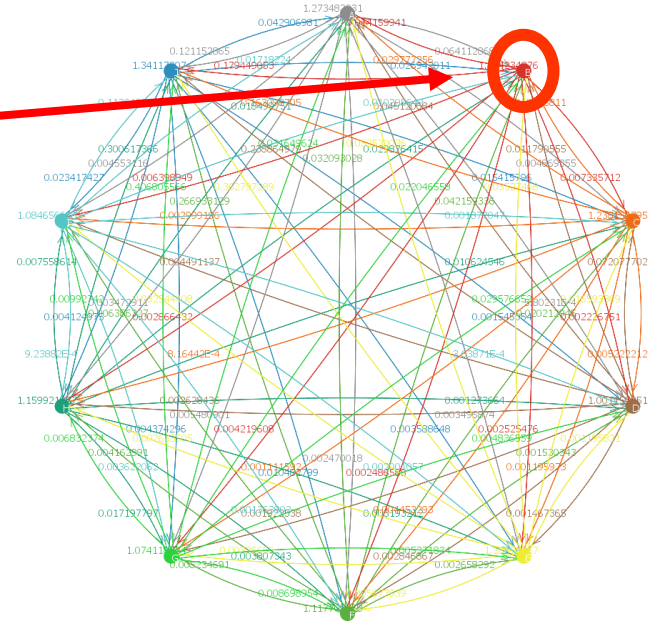
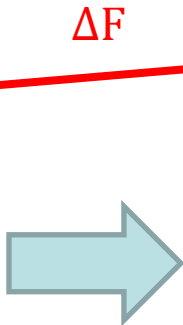
- Disadvantage
 - Insufficient as I/O model is unable to describe real physical infrastructure network

→ To link actual physical infrastructure network with I/O model

Interfacing actual physical infrastructure network with I/O interdependency network



Actual physical telecommunication network



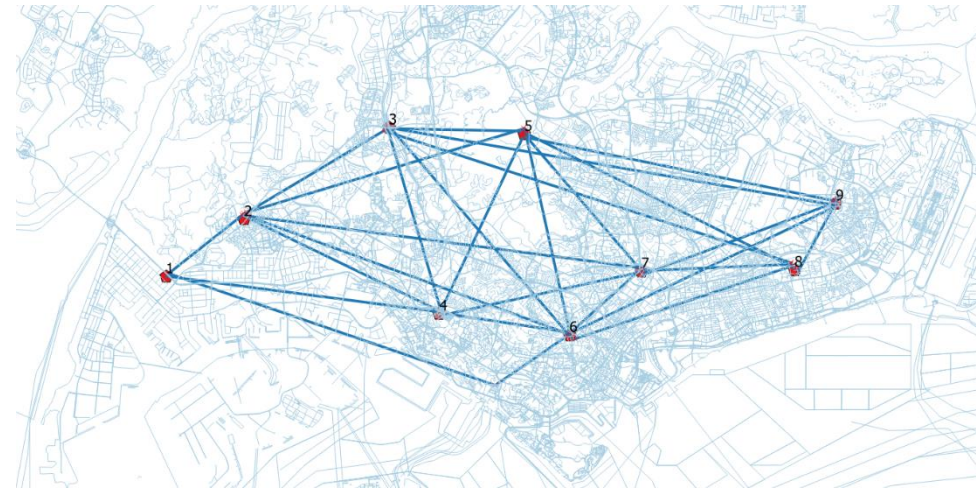
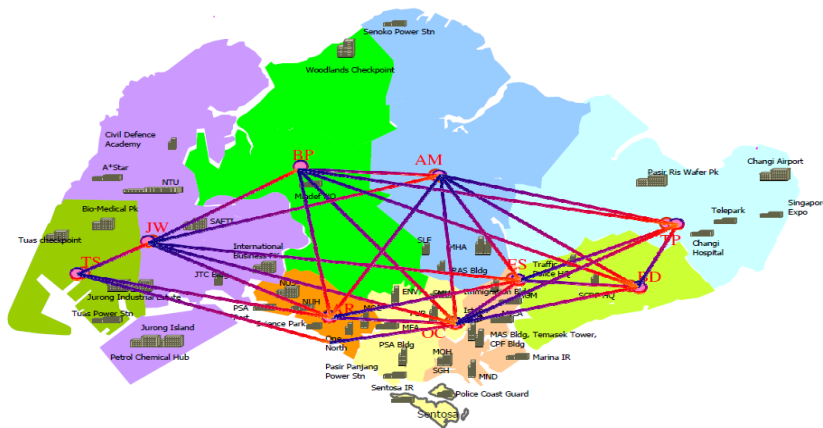
I/O interdependency network model

Construction of physical infrastructure network

- Information and Telecommunications as CI
- ## Central Offices - Core Network

9 COs proposed :

- ✓ Excellent geographical spread;
- ✓ Shortest Deployment Time;
- ✓ Resilient, Robust, Reliable Design



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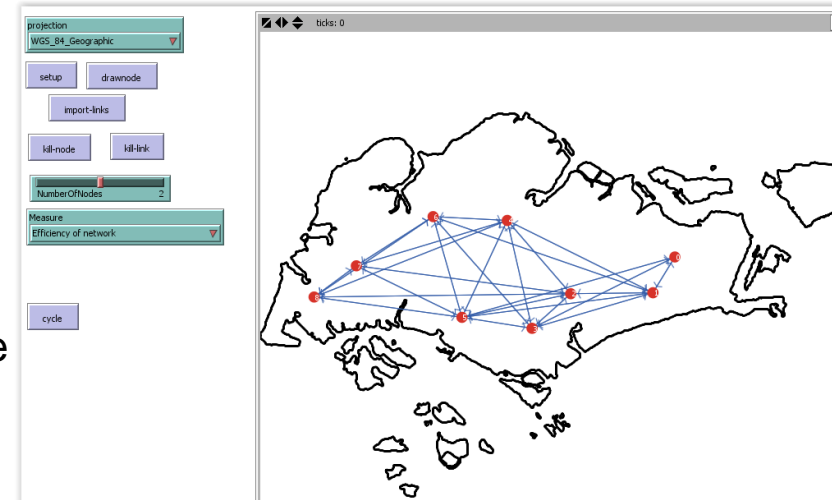
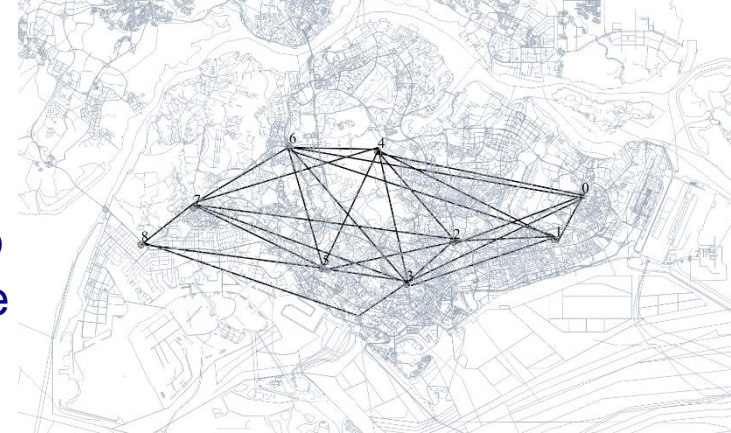
OpenNet

Map recreated in QGIS for location targeting

*OpenNet. *Technical Architecture Of NGNBN & Fibre Coverage*. Tiong Onn Seng. 30th July 2009

Simulation process

- The hazard is represented by failure of nodes in physical infrastructure network
 - Terrorist attack (Targeted node)
 - Disaster (Area damage)
- A complete search of the worst case scenario of 1,2,3 node failure for physical infrastructure is being setup
- Program used:
 - QGIS
 - For GIS location of physical infrastructure
 - Matlab
 - As main computation engine
 - Excel
 - For data management
 - Netlogo
 - For simulation of physical infrastructure failure



Initial network performance

- **Initial network performance** is calculated for the given physical infrastructure network
- Network performance can be measured by:

1. Efficiency of network

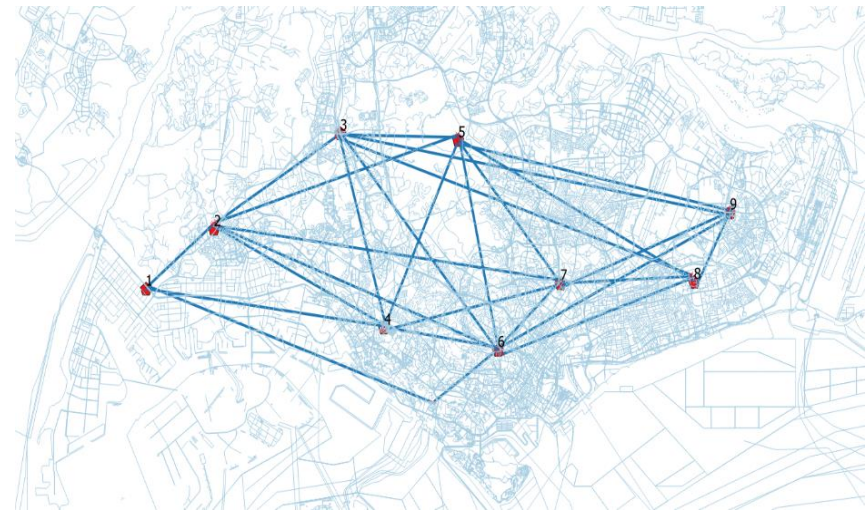
- n denotes the total number of nodes and $d(i, j)$ denote the shortest path between a node i and a neighboring node j .

$$E(G) = \frac{2}{n(n-1)} \sum_{i,j \in G} \frac{1}{d(i, j)}$$

2. Network average clustering coefficient

- The average of the local clustering coefficients of all the vertices n .

$$\bar{C} = \frac{1}{n} \sum_{i=1}^n C_i$$



Telecommunication network in Singapore

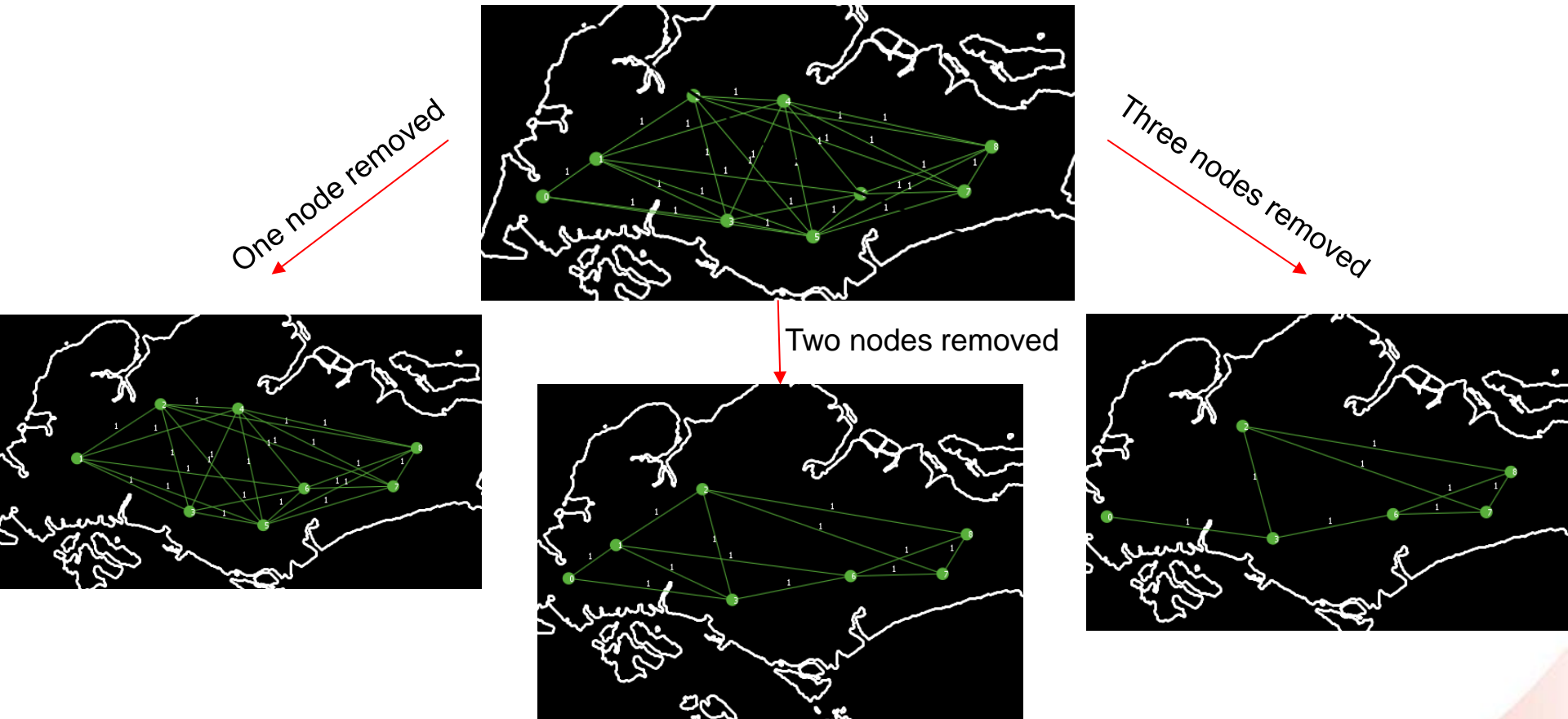
Efficiency of network:

P. Crucitti, V. Latora, and M. Marchiori, "Model for cascading failures in complex networks," *Physical Review E*, vol. 69, p. 045104, 2004.

Network average clustering coefficient:

Z Mao, L Hong, Q Fei, M OuYang - *Advances in Neural Networks—ISNN 2009*, 2009

Final network performance



Calculate new network performance of the new network structure based on the 2 network performance measures

Measure losses in network performance

- Losses in network performance would be

$$e(Loss) = \left(1 - \left(\frac{Efficiency(new)}{Efficiency(initial)}\right)\right) * 100\%$$

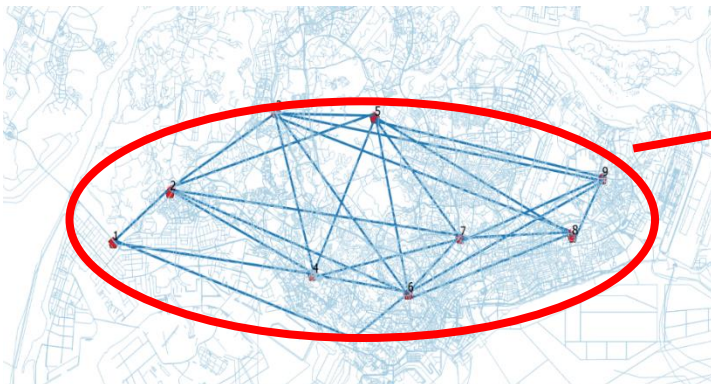
- If the efficiency of the network after a node removal is low, the removed node is critical. [e(loss) will be positive]

Calculate economic losses in the network

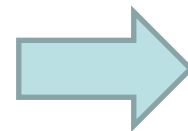
- We assume that for each hour failure of a physical infrastructure, it will incur losses in the form of:

$$i(loss) = \frac{x_i}{365 * 24} * e(loss)$$

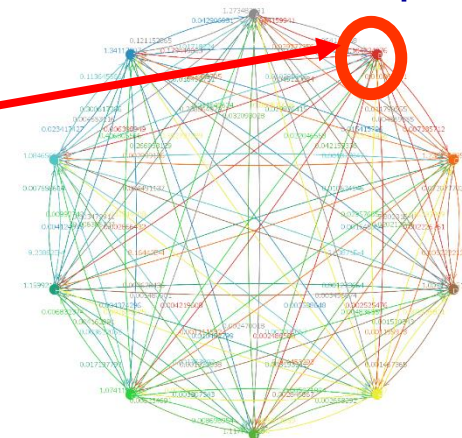
- $i(loss)$ = Monetary loss for an infrastructure sector
- x_i = Output of the sector i in a year
- $e(loss)$ = Percentage loss of the failed infrastructure.
- $i(loss)$ will be used in ΔF in I/O model, and thus ΔX can be computed



Actual physical telecommunication network



ΔF



I/O interdependency network model

Results

% impact to
singapore hourly

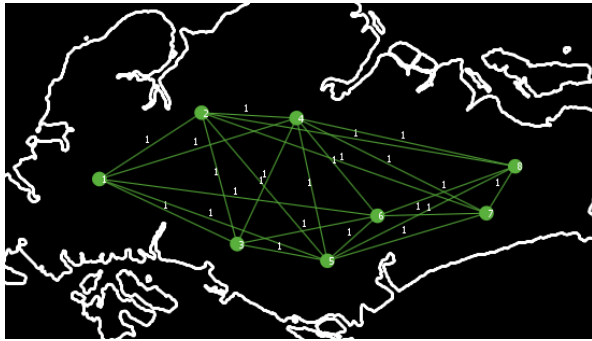


Table 1. Results of the top 3 worst case scenarios for one-node failure

Network performance scheme	Failure scenario	η_{initial}	η_{new}	e_{loss}	Overall impact, ΔX (\$ Millions)	% impact to Singapore hourly
Efficiency of network	[0]	1.28	1.18	7.76	6.94	4.9%
	[7]	1.28	1.25	2.17	1.94	1.4%
	[8]	1.28	1.25	2.17	1.94	1.4%
Network average clustering coefficient	[5]	0.793	0.717	9.64	8.62	6.1%
	[4]	0.793	0.730	7.99	7.14	5.1%
	[7]	0.793	0.796	-0.342	-0.306	-0.2%



Table 2. Results of the top 3 worst case scenarios for two-node failure

Network performance scheme	Failure scenario	η_{initial}	η_{new}	e_{loss}	Overall impact, ΔX (\$ Millions)	% impact to Singapore hourly
Efficiency of network	[0 1]	1.28	1.14	10.6	9.44	6.7%
	[0 3]	1.28	1.14	10.6	9.44	6.7%
	[0 7]	1.28	1.14	10.6	9.44	6.7%
Network average clustering coefficient	[4 5]	0.793	0.571	28.0	25.0	17.8%
	[1 5]	0.793	0.576	27.4	24.4	17.4%
	[3 5]	0.793	0.576	27.4	24.4	17.4%



Table 3. Results of the top 3 worst case scenarios for three-node failure

Network performance scheme	Failure scenario	η_{initial}	η_{new}	e_{loss}	Overall impact, ΔX (\$ Millions)	% impact to Singapore hourly
Efficiency of network	[0 1 3]	1.28	1.07	16.5	14.8	10.5%
	[0 7 8]	1.28	1.07	16.5	14.8	10.5%
	[1 3 5]	1.28	1.10	13.9	12.4	8.9%
Network average clustering coefficient	[1 4 5]	0.793	0.333	58.0	51.8	36.9%
	[3 4 5]	0.793	0.333	58.0	51.8	36.9%
	[4 5 8]	0.793	0.444	44.0	39.3	28.0%

The worst case scenario that causes largest impact is found

Concluding remarks

- This framework provides a quick method to model and analyse critical infrastructure interdependencies
 - In situation where expert data is unavailable, this approach can still be used
- Interfacing physical infrastructure and I/O interdependency model facilitates modeling of various scenarios in the physical world
- Simulation shows its capability of finding worst case scenario to aid decision-making for stakeholders and security service provider to protect the infrastructures accordingly
 - With limited resources, need to prioritise which infrastructure assets to receive more protection
- Future work will be on a case study to validate this model

Thank you for attending this presentation!
Comments/Suggestions are appreciated.