

Evaluation of air transportation network resilience using adaptive capacity

The Conference on Traffic and Granular Flow 2015
2015.10.28

Suhyung Yoo and Hwasoo Yeo*
Dept. of Civil and Environmental Eng. in KAIST, South Korea

1. Introduction

Air transportation is one of major transport modes to carry both passengers and freight.

Source

Federal Aviation Administration Statistics in 2014

8.5 Million flights



662 M Passengers



20,305 M lbs

1. Introduction

A single failure of ATN can bring a huge socio-economic impact.

In 2010

Iceland

Eyjafjallajökull
Volcano Eruption

Volcanic ash covered north Europe
During the One week

Cancelled **60 thousands** flights

Economic Loss **170 M** dollars



Photo taken by ©lafur Eggertsson

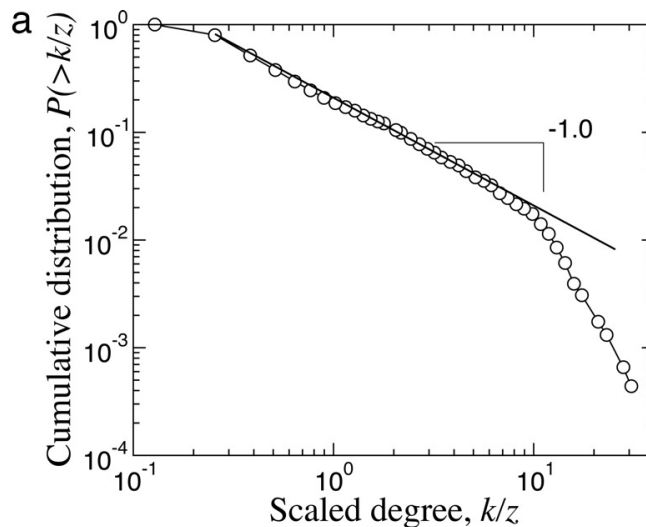
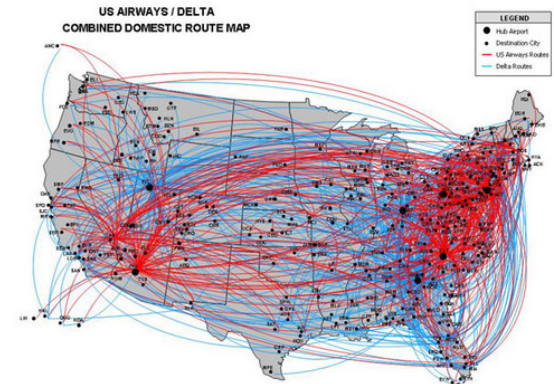


Reference: BBC News, 16 April 2010 and Source from Met Office

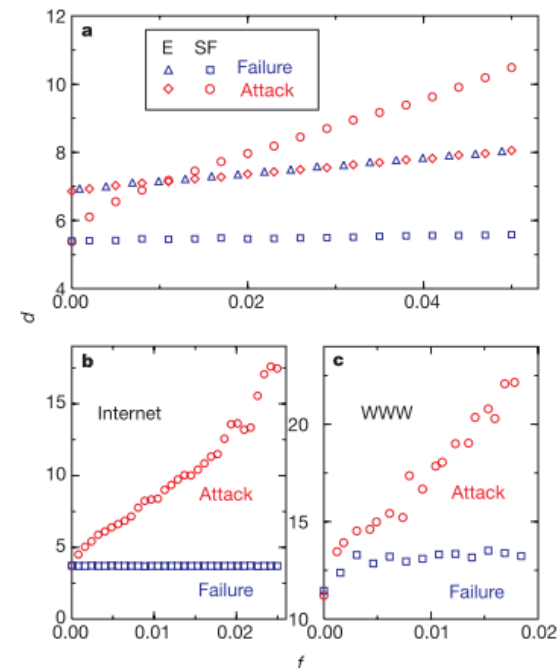
1. Introduction

ATN is a well-known scale-free network, which is robust to random hazard but vulnerable to targeted attack

- A random hazard has a small chance of removing a high h-degree node, but an informed agent will target high st-degree node (Albert et al. 2000)
- So it has the inherent hazard tolerance of the network (Barabasi and Oltvai 2004)



R. Guimera et al, "The Worldwide air transportation network :Anomalous centrality community structure, and cities' global roles," *PNAS*, vol. 102, no. 22, May, 2005



R. Albert, H. Jeong, and A. Barabási, "Error and attack tolerance of complex networks," *Nature*, vol. 406, no. July, 2000

1. Introduction

Definition of **Resilience**

- The ability of a system to return to a stable state following a strong perturbation caused by failure, disaster or attack

C. S. Holling, "Engineering resilience versus ecological resilience," *Eng. within Ecol. constraints*, no. 1996, pp. 31–43, 1996

- Ability to withstand and stay operational at the required level of safety during the impact of a given disruptive event

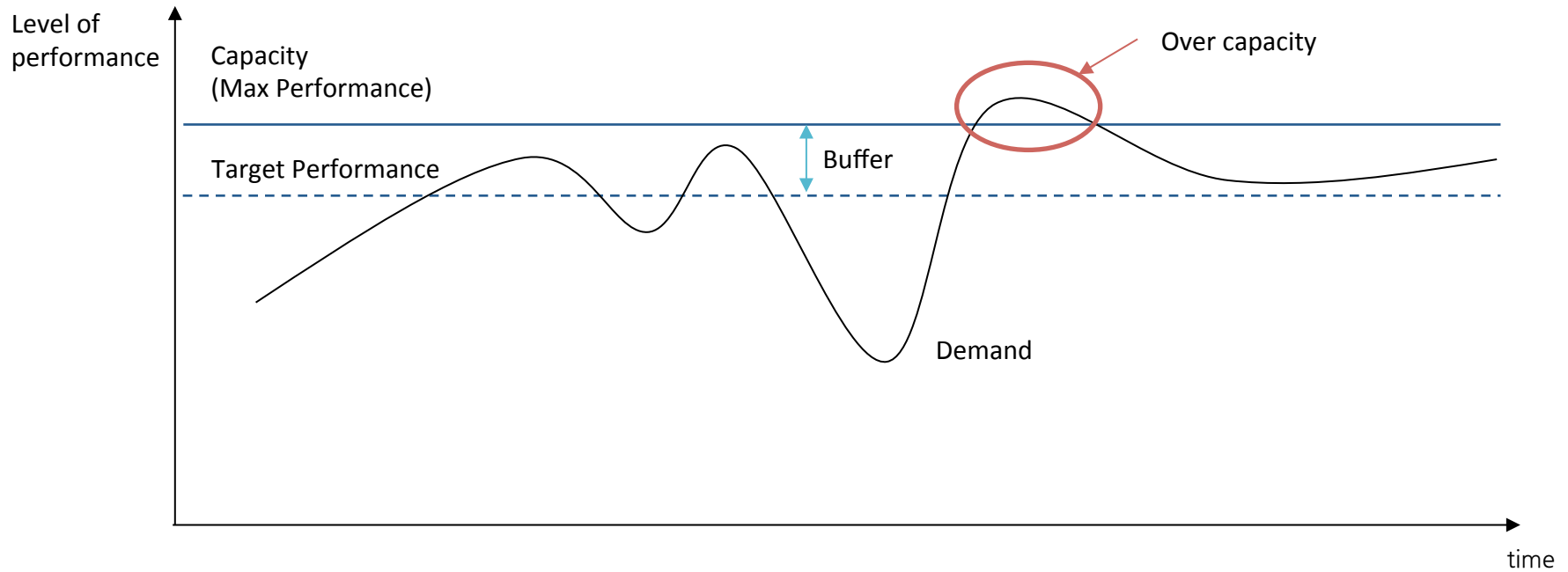
M. Zanin and F. Lillo, "Modelling the air transport with complex networks: A short review," *Eur. Phys. J. Spec. Top.*, pp. 1–28, 2013.



- Adaptive capacity is the ability or potential of a system to respond successfully to variability and change, and includes adjustments in both behavior and in resources and technologies.
- The presence of adaptive capacity has been shown to be a necessary condition for the design and implementation of effective adaptation strategies so as to reduce the likelihood and the magnitude of harmful outcomes resulting from the change. (Brooks and Adger, 2005)

1. Introduction

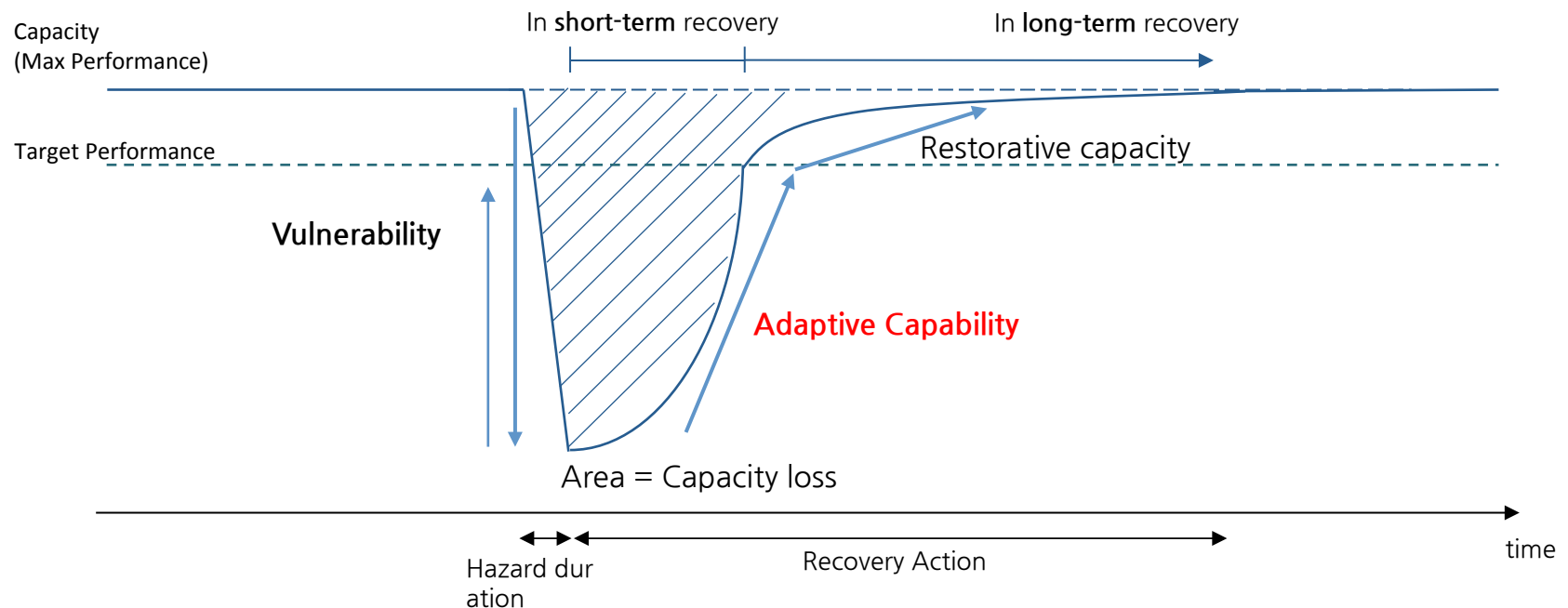
Resilience of system



An infrastructure usually remain some buffer to prepare the change of demand

1. Introduction

Resilience of system: What if supply changes?



Absorptive capacity: the ability of the system to absorb the disruptive event

Adaptive capacity : the degree to which the system is capable of self-organization for recovery of system performance levels

Restorative capacity : the ability of the system to recover/be repaired

Ref. A framework for Assessing the Resilience of Infrastructure and Economic Systems, Eric D. Vugrin et al., 2010

1. Introduction

The network ability to maintain a certain level of performance is essential as to provide sufficient and satisfactory service, so this paper will evaluate the network resilience to a perturbation.



Goal of this paper

1. Suggest to measure 'adaptive capacity' for evaluating network resilience

- System's performance change (increased travel time, economic loss) is hard to measure although it contains effect of short-term recovery
- We regard the resilience is to sustain a target performance level when a perturbation disturbs the network, and is come from the replacing capability of its remained part of the system

2. Identify less resilient part of system in ATN

- Adaptive capacity index help us to identify less resilient part of the system
- Identify Previous studies focused on the vulnerability by measuring impact of each node/link

2. Methodology

Air Transportation Network

Network Structure

- Node : Airport
- Edge : Air route in schedule
- Agent : Air flight
- Weight : Scheduled flights

Characteristic

- Scale-free network which has a few hub airports
- Spatial network where the nodes are located in physical space
- With nodes which have a capacity to function of a system
- With low cost of link connection

Related researches

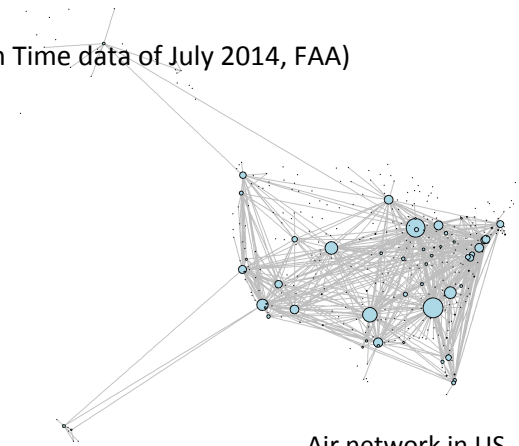
- A. Barrat, M. Barthélemy, R. Pastor-Satorras, and A. Vespignani, "The architecture of complex weighted networks," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 101, no. 11, pp. 3747–52, Mar. 2004.
- R. Guimerà, S. Mossa, A. Turtshi, and L. A. N. Amaral, "The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 102, no. 22, pp. 7794–9, May 2005.
- S. M. Wilkinson, S. Dunn, and S. Ma, "The vulnerability of the European air traffic network to spatial hazards," *Nat. Hazards*, vol. 60, no. 3, pp. 1027–1036, 2012.
- M. Janić, "Modelling the resilience, friability and costs of an air transport network affected by a large-scale disruptive event," *Transp. Res. Part A Policy Pract.*, vol. 71, pp. 1–16, 2015.
- E. K. Morlok and D. J. Chang, "Measuring capacity flexibility of a transportation system," *Transp. Res. Part A Policy Pract.*, vol. 38, no. 6, pp. 405–420, Jul. 2004.
- M. Zanin and F. Lillo, "Modelling the air transport with complex networks: A short review," *Eur. Phys. J. Spec. Top.*, pp. 1–28, 2013.

2. Methodology

Simulation

- A weighted, undirected graph with nodes(airports) and links(air routes)
- Data : Air transportation statistics from Federal Aviation Administration in United States, where there are 296 primary airports and 9,273 connections in 2014
- Node(Airports) : State, FAA code, Enplanement, Geo-location, Capacity based on condition
- Link(Air routes) : Origin, Destination, Departure time, Arrival time
 - Link exists if there is at least one flight departing or arriving to the node
- Weight(Flights) : Number of flights departing or arriving to the airport per hour

Using data of hourly average in July 2014 (On Time data of July 2014, FAA)

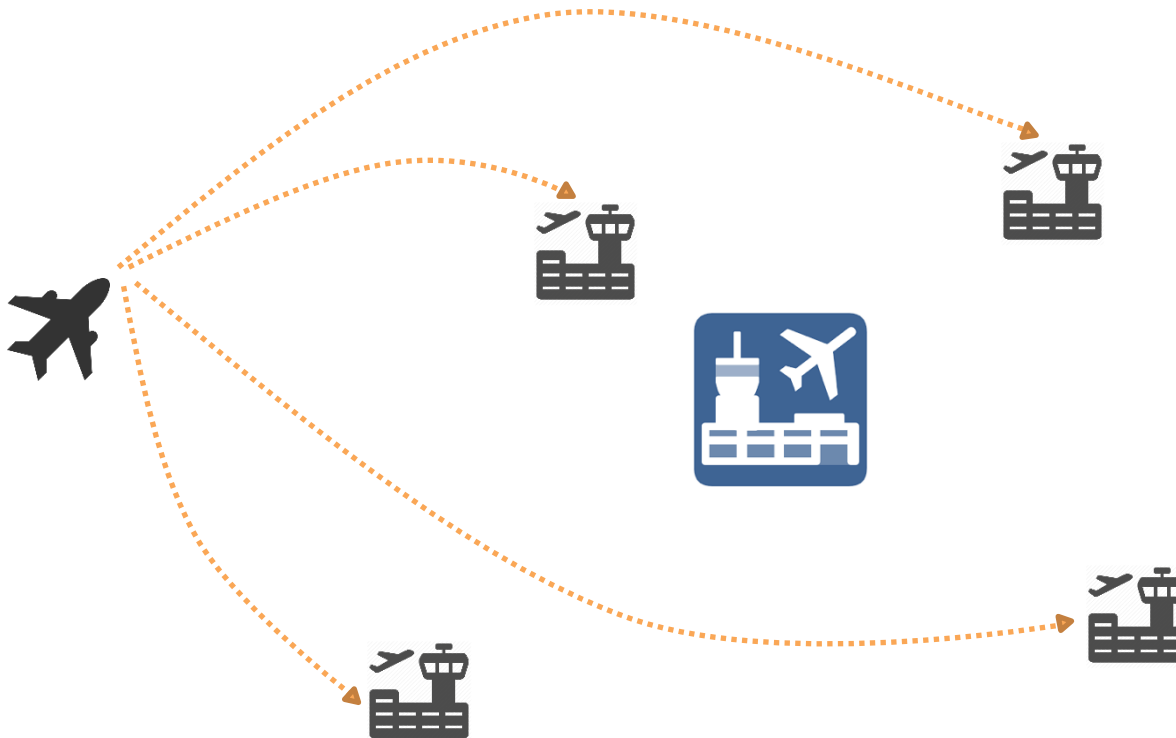


Air network in US

2. Methodology

Simulation

- Key concept: the ability of a network in which an attacked node can be replaced by other adjacent nodes



2. Methodology

Simulation

In initial state : the system is in its stable condition in which each node functions lower than its capacity. So congestion does not occur.

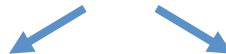


Event

A disruptive event occurs and brings a **failure of node**. Simulation removes the node from the system and then connected links become disabled.



Changing not only network topology but also balance of capacity and flow, the system redistributes the failed node's function to adjacent nodes to replace it.



Resilient case :

If other nodes have enough margin to handle the redistributed loads, the network is still capable of performing with level of initial state

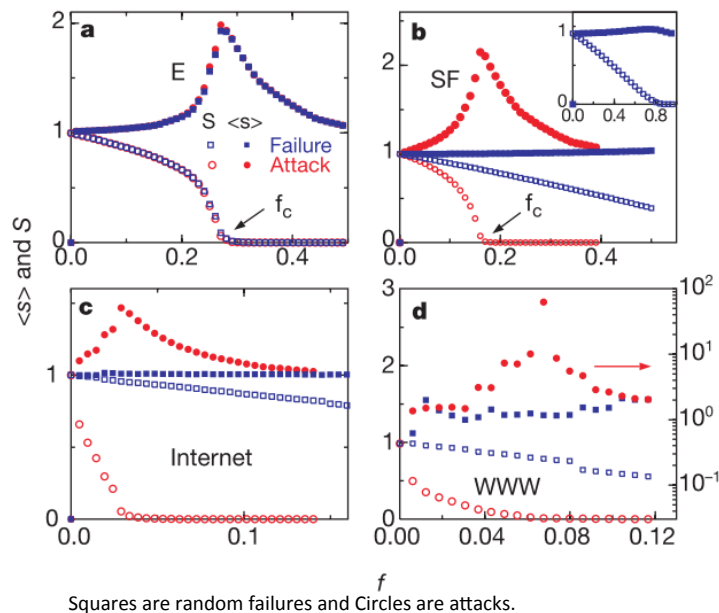
Less resilient case :

But the load exceeds remaining margin, it brings about a large drop of network performance and a network failure

2. Methodology

Type of damages

- 1. Single: a point hazard
 - Error, strike, accident
- 2. Simultaneous: a serial/sequential attack
 - weather(spatial damage), terror attack(order of importance)



R. Albert, H. Jeong, and A. Barabási, "Error and attack tolerance of complex networks," *Nature*, vol. 406, no. July, 2000

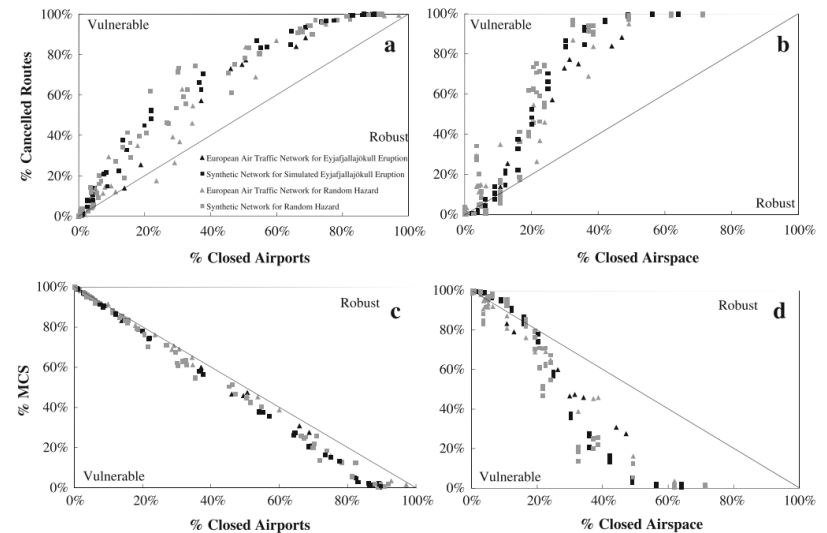


Fig. 6 Comparison of network vulnerability for the EATN and our three synthetic networks, showing **a** the impact of airport closure on air route operations; **b** the influence of airspace closure on air route operations; **c** the reduction in MCS due to airport closures; and **d** the influence of airspace closure on MCS

S. M. Wilkinson, S. Dunn, and S. Ma, "The vulnerability of the European air traffic network to spatial hazards," *Nat. Hazards*, vol. 60, no. 3, pp. 1027–1036, 2012

2. Methodology

Index

- The index of adaptive capacity to measure the network resilience
: How the network can react to the shock and divide work load
- Under a single failure

k/a (Degree of adaptation)

Number of required nodes that need to replace the flow

$$Flow_{hub} \leq \sum_{i=1}^k Margin_i \quad (i : \text{order of Euclidean distance from}$$

m the attacked node)

r/a (Radius of adaptation area)

Range of redistributed flow receiver nodes

$$k^{th} \text{ node's distance from } Flow_{hub} \leq \sum_{i=1}^k Margin_i$$

$cost/unit$ (Unit cost of adaptation)

Cost in terms of additional detoured distance for each flight

$$\sum_{i=1}^n Distance_i * ReassignedFlow_i / \sum Reassigned$$

$Flow$

$cost/total$ (Cost of adaptation)

Total detoured distance for all redistributed flights

$$\sum_{i=1}^n Distance_i * ReassignedFlow_i$$

2. Methodology

Index

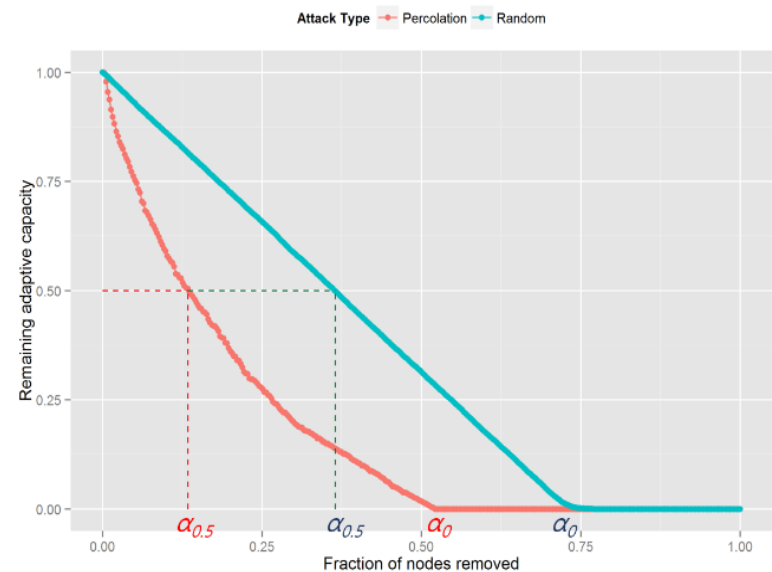
- The index of adaptive capacity to measure the network resilience : How the network can react to the shock and divide work load
- Under a simultaneous attack

Remaining Adaptive Capacity

- How much extra work load the network can handle
- The ratio of remaining margin to initial margin of the network

Alpha Index

- The lines reach their bottom at different x-axis, which we call alpha zero
- Alpha zero (α_0) is the fraction of nodes at which the network cannot afford to absorb the extra load
- It give us better understating of network's fragility

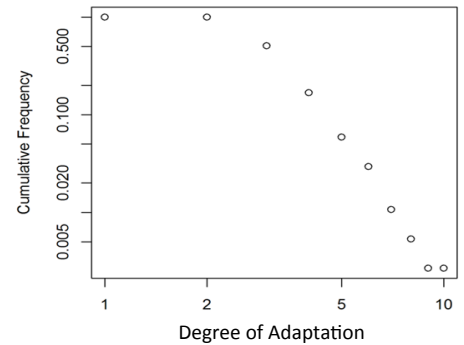
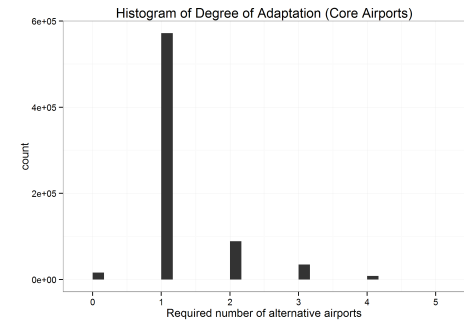
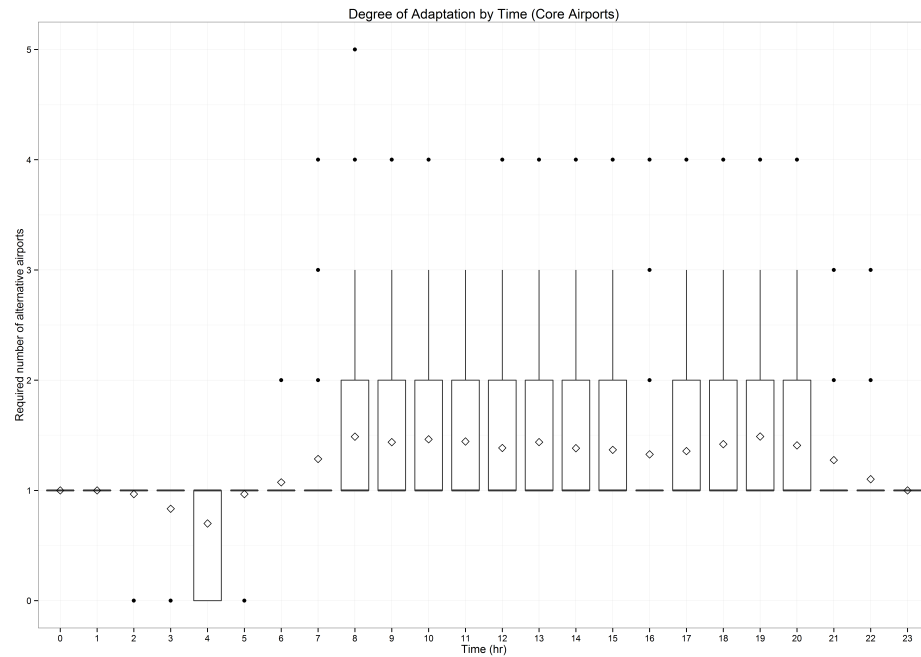


3. Results

Air Transportation Network Resilience Under a Single Failure (Core Airports)

Degree of Adaptation

- Depending of the time, the required number of alternative airports are changed and so that the degree of adaptation varies by time.
- Max. 5 to Min. 0

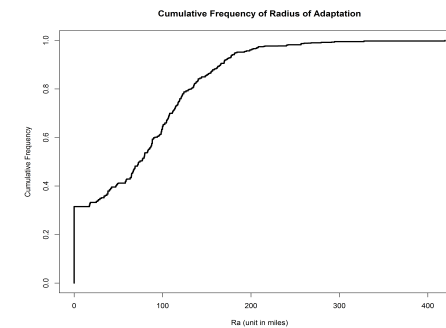
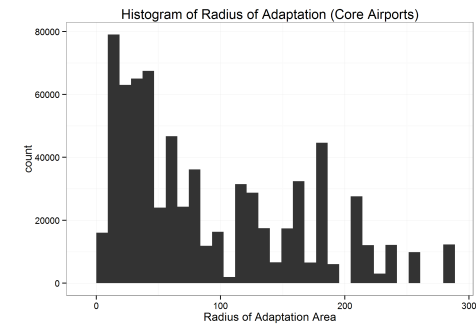
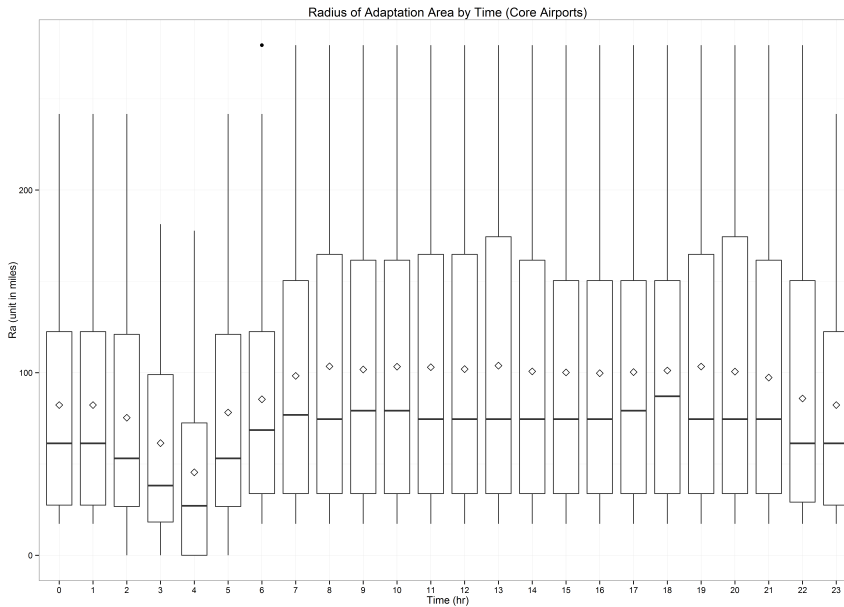


3. Results

Air Transportation Network Resilience Under a Single Failure (Core Airports)

Radius of Adaptation Area

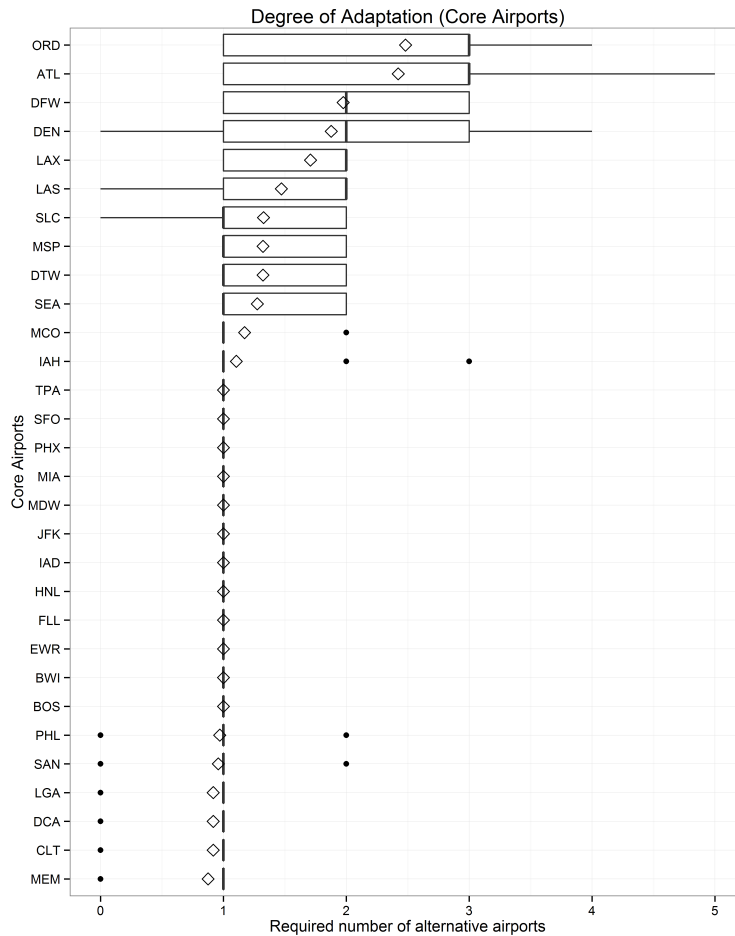
- The radius of adaptation area varies by each airport rather than by time
- It may be depend on sub-network's topology



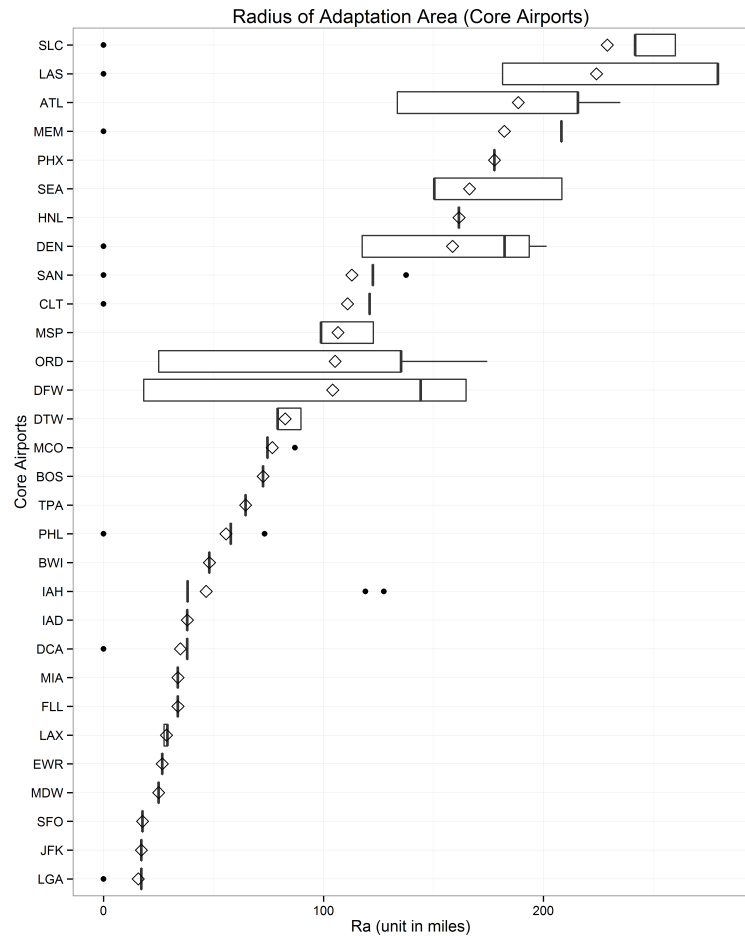
3. Results

Air Transportation Network Resilience Under a Single Failure (Core Airports)

ORD, ATL, DFW



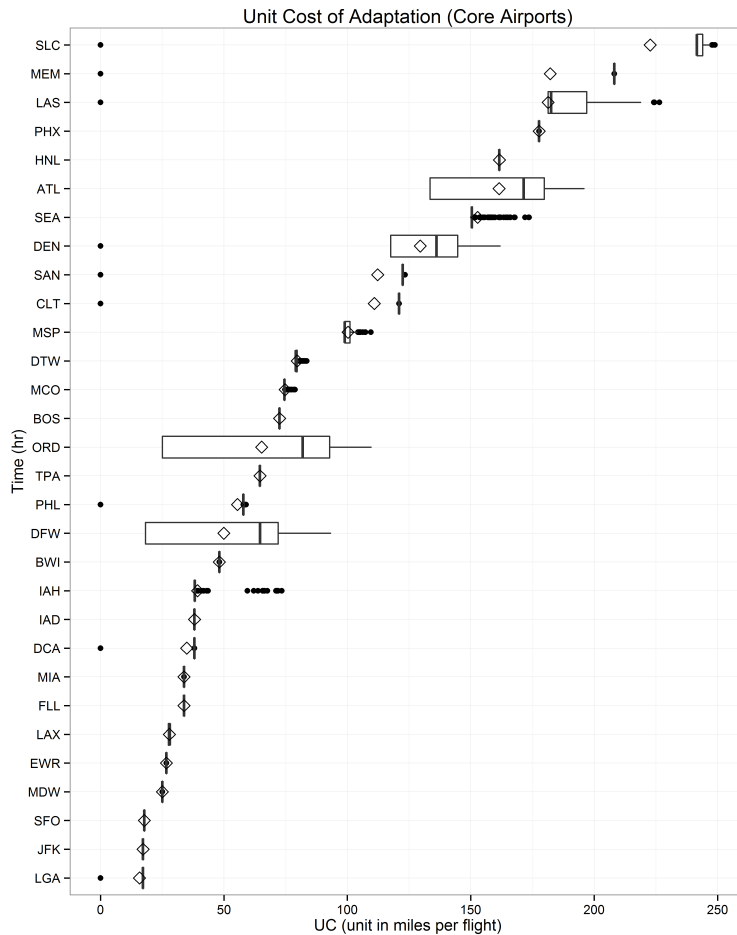
SLC, LAS, ATL



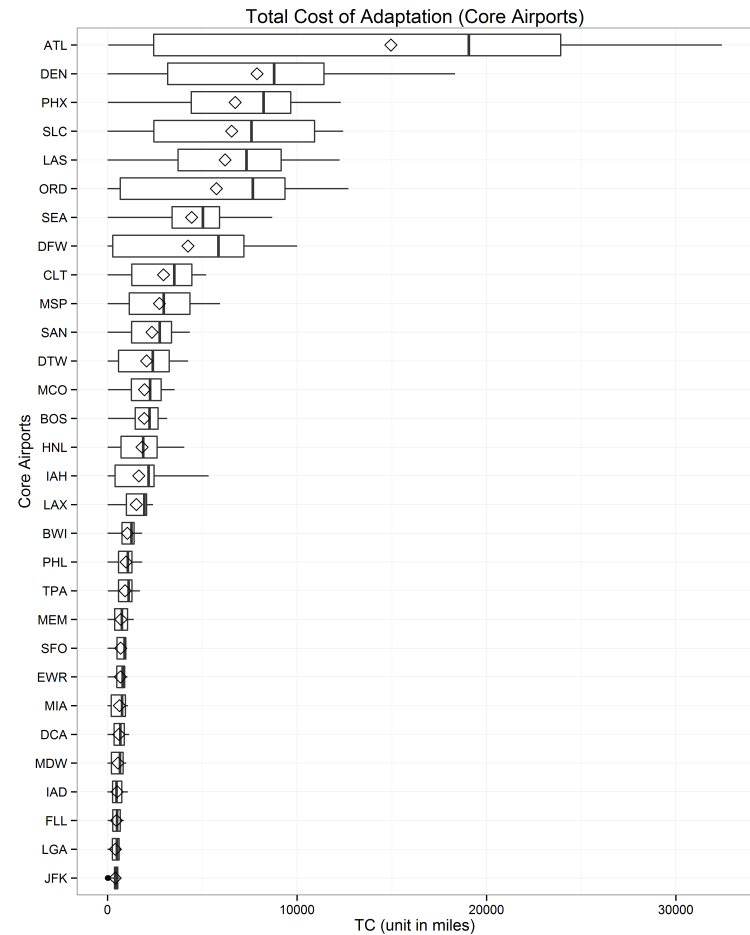
3. Results

Air Transportation Network Resilience Under a Single Failure (Core Airports)
- Considering effect of weights

Average detoured distance



Total detoured distance of all rescheduled flights

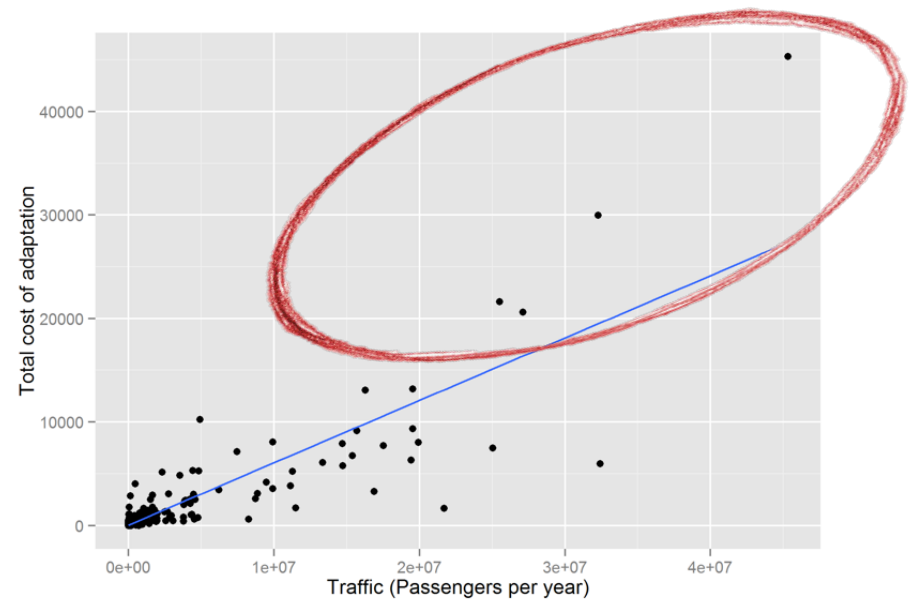
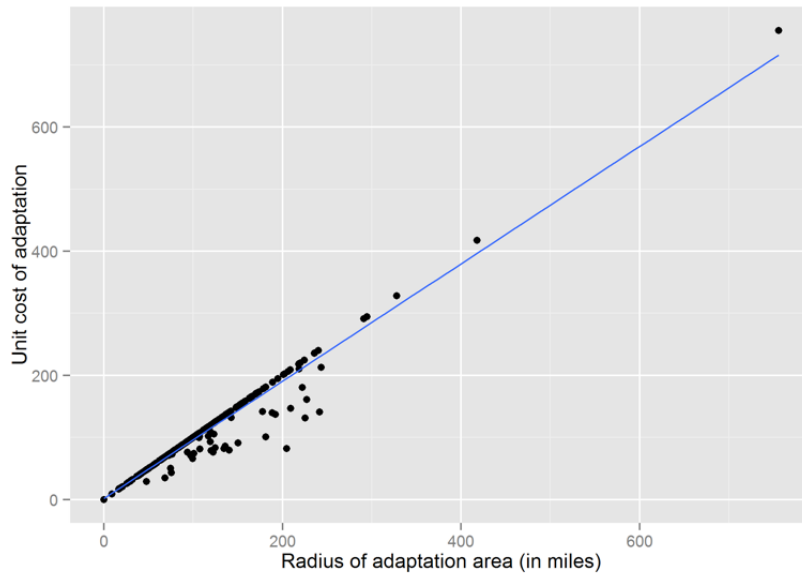


3. Results

By their definition, the radius index and unit cost of adaptation / the traffic volume and total cost of adaptation are closely related

Then, we can identify outliers over the regression line

RANK				
1	ORD	DUT	DUT	ATL
2	ATL	FAI	FAI	ORD
3	DEN	BRW	BRW	DEN
4	DFW	SCC	SCC	DFW
5	EWR	OTZ	OTZ	CLT



Correlation between radius of adaptation area and unit cost of adaptation (left), traffic and total cost of adaptation(right)



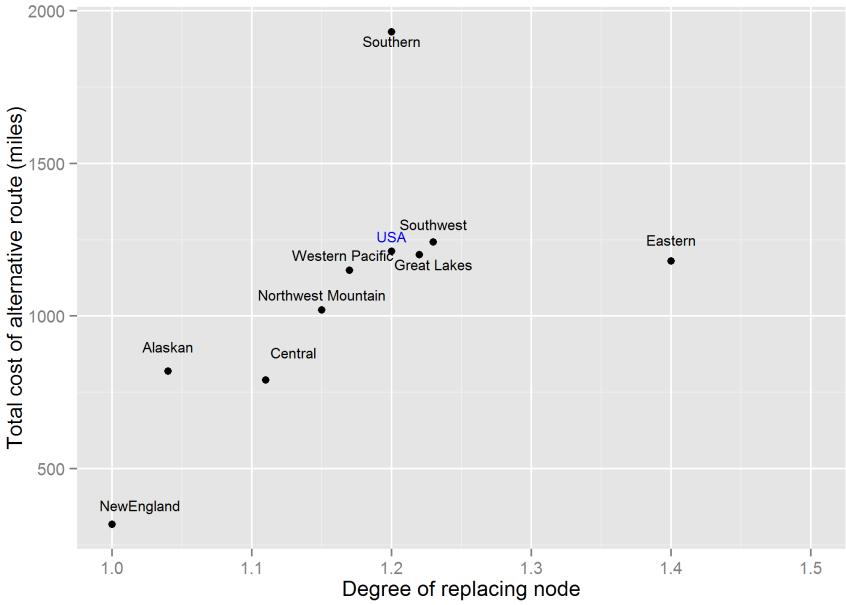
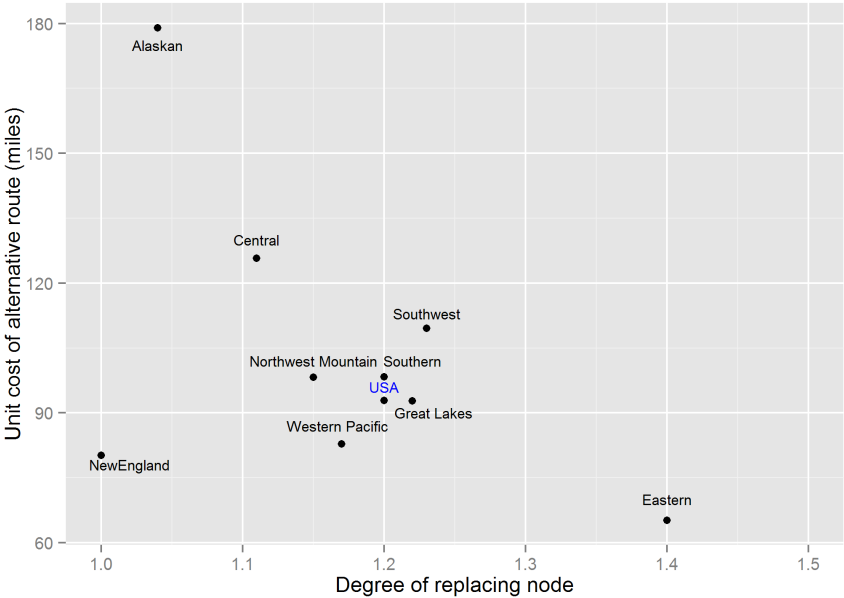
3. Results

By sub regions

FAA categorized airports into 9 regions

Our index can identify vulnerable and resilient region c
ompared to the average of USA.

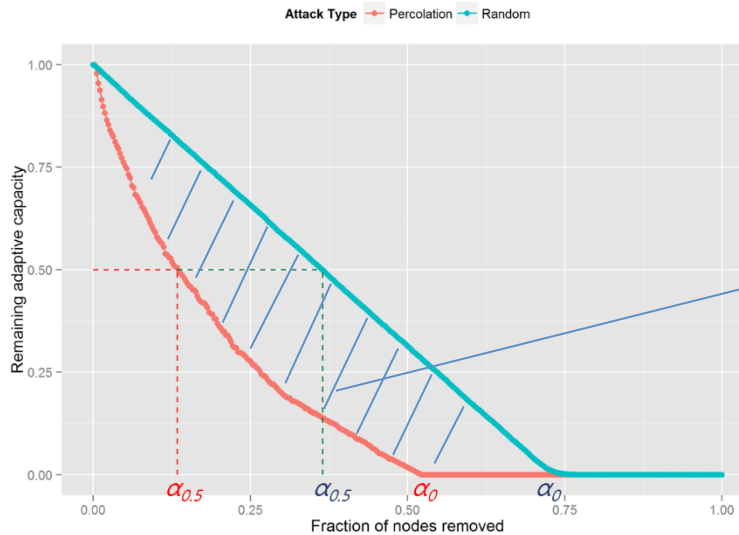
REGION				
Alaskan	1.04	180.7	178.9	819.8
Central	1.11	130.8	125.7	790.5
Eastern	1.40	69.8	65.2	1180.3
Great Lakes	1.22	96.4	92.8	1200.5
New England	1.00	80.2	80.2	318.3
Northwest Mountain	1.15	102.6	98.2	1020.6
Southern	1.20	95.2	92.9	1931.2
Southwest	1.23	115.0	109.5	1242.4
Western Pacific	1.17	87.8	82.8	1149.6
USA	1.20	102.1	98.3	1212.2



3. Results

- Attack a node one by one until all nodes are extracted (percolation)
- Comparison of random failure and targeted attack
- Random attack result come from average of 100 repeats

Targeted attack in order of the importance of node

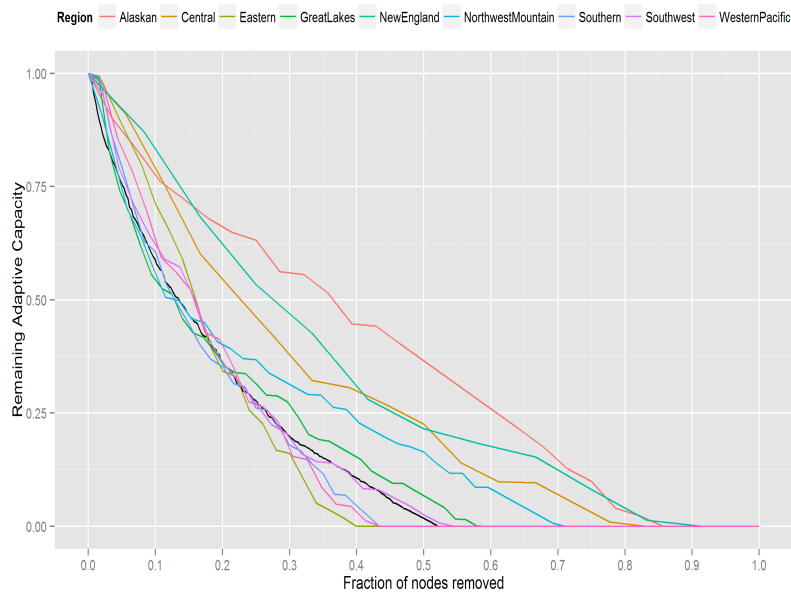


Area

- Difference caused by targeted attack
- Network with bigger area tends to have more vulnerability / less robustness

3. Results

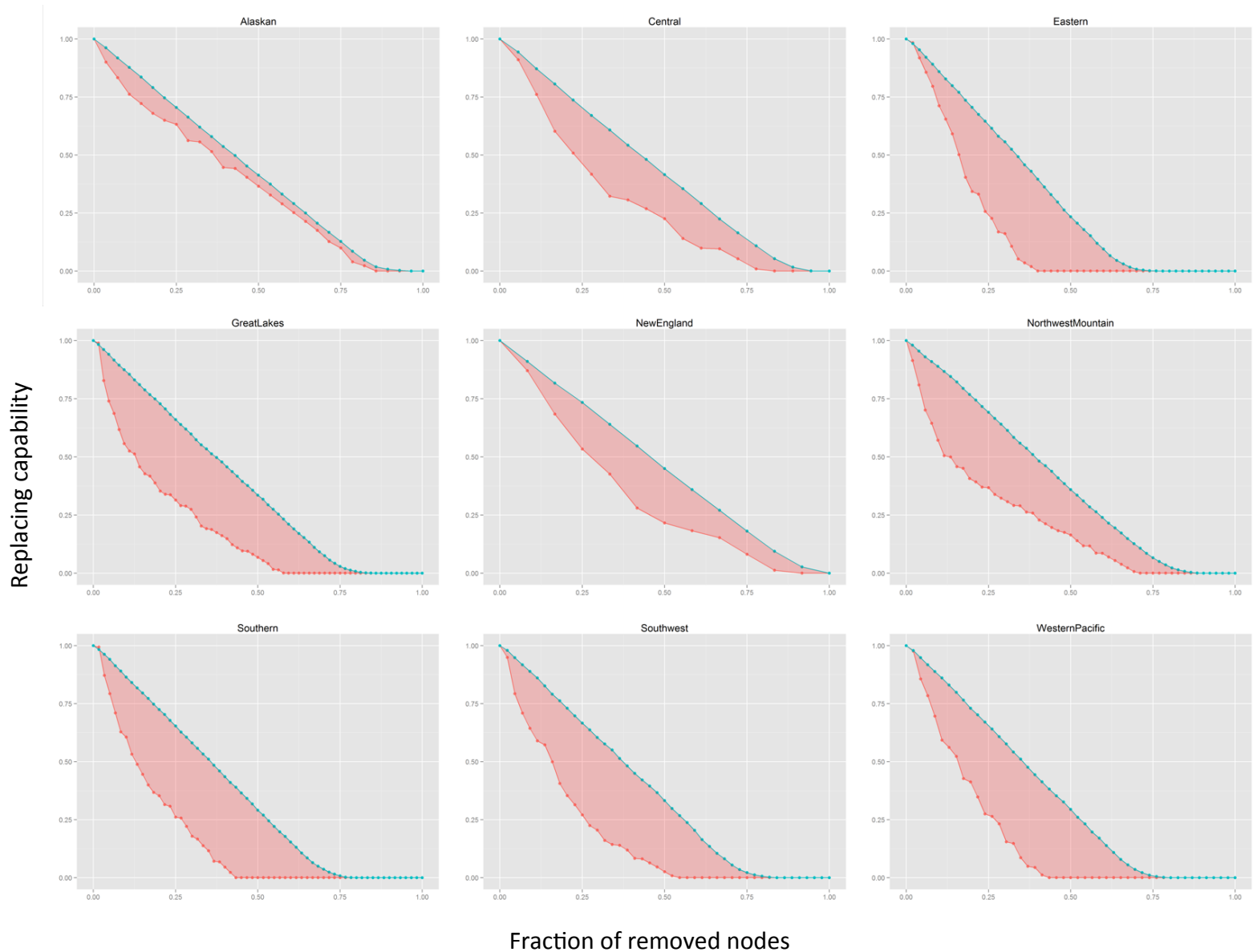
- Attack a node one by one until all nodes are extracted (percolation)
- Comparison of random failure and targeted attack
- Random attack result come from average of 100 repeats



Region	$\alpha_{0.5}$	α_0	Index of adaptive capacity
USA	0.13	0.52	0.48
Alaskan	0.36	0.86	0.88
Central	0.22	0.83	0.66
Eastern	0.16	0.4	0.51
Great Lakes	0.12	0.59	0.50
New England	0.25	0.92	0.71
Northwest Mountain	0.13	0.71	0.56
Southern	0.13	0.45	0.46
Southwest	0.16	0.55	0.48
Western Pacific	0.15	0.43	0.48

Figure 5 Regional sub-network's replacing capability against node removals under percolation attack. Each region has different profile showing diverse slopes. USA whole network's profile is represented as black line to compare with.

3. Results



4. Conclusion

- This paper introduced the new index to quantify the resilience of networks from a perspective of adaptive capacity
- Adaptive capacity can capture a load factor of undesired hazard in terms of 1) required number of nodes to maintain targeted performance level 2) furthestmost distance to detour 3) average detoured distance 4) total detoured distance
- Identified less resilient airports and sub-regions are needed further study, what are the factors to make them vulnerable. But we found a clue that network topology and traffics are closely related to their resilience.

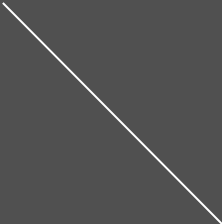
Application

- Help to make priority of where the most need gov.'s care
- Evaluate effective strategies to increase network resilience:
Increasing capacity of an airport, Constructing alternative airport to share burden, Relocating(rescheduling) flight and so on.



Thank you for listening

Questions:
suhyung.yoo@kaist.ac.kr



Appendix.

To evaluate vulnerability of the system, researchers measure the impact of a disruptive event

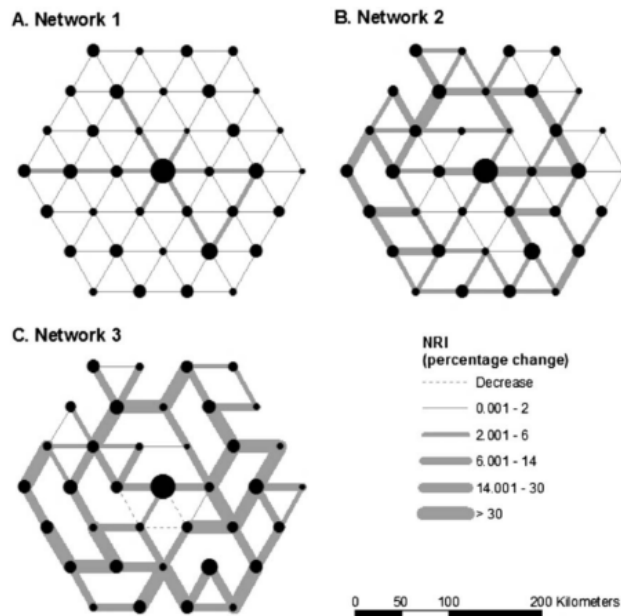
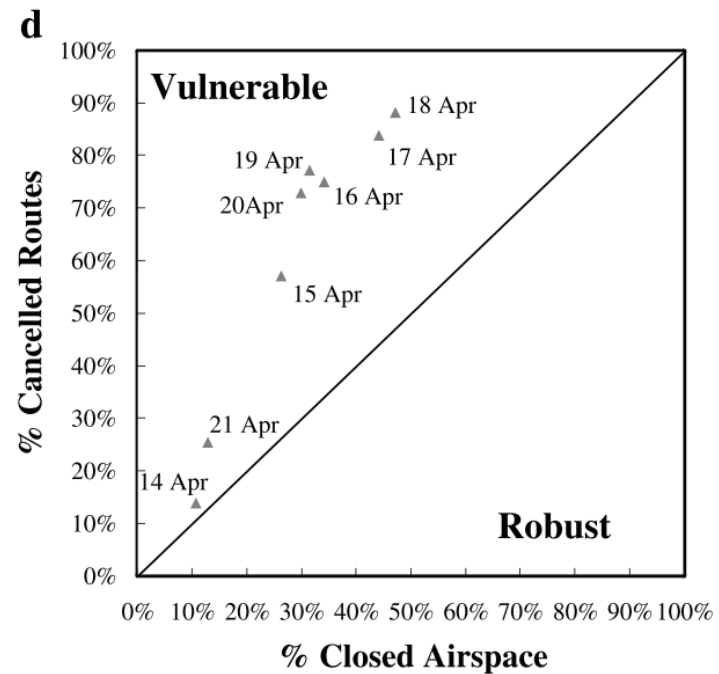


Fig. 3. NRI expressed in terms of percentage change from each network's base case.

Evaluating importance of a link in terms of increasing travel time under removal of a link



Proportion of travel disruption relative to the proportion of closed airspace during Eyjafjallajökull eruption