Building Resilience into Fragile Transportation Networks in an Era of Increasing Disasters

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Disaster Recovery and Mitigation Planning and Resilience

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Special acknowledgments and thanks to my students and collaborators who have made research and teaching always stimulating and rewarding.

Transportation networks are the *fundamental critical infrastructure* for the movement of people and goods in our globalized *Network Economy*.

Transportation networks also serve as the primary conduit for *rescue, recovery, and reconstruction in disasters.*

Recent disasters have vividly demonstrated the importance and vulnerability of our transportation and critical infrastructure systems

- The biggest blackout in North America, August 14, 2003;
- Two significant power outages in September 2003 – one in the UK and the other in Italy and Switzerland;
- The Indonesian tsunami (and earthquake), December 26, 20o4;
- Hurricane Katrina, August 23, 2005;
- The Minneapolis I35 Bridge collapse, August 1, 2007;
- The Mediterranean cable destruction, January 30, 2008;
- The Sichuan earthquake on May 12, 2008;
- The Haiti earthquake that struck on January 12, 2010 and the Chilean one on February 27, 2010;
- The recent floods in northeastern Australia and Brazil and the accompanying mudslides in the latter.

Hurricane Katrina in 2005

Hurricane Katrina has been called an *"American tragedy,"* in which essential services failed completely (Guidotti (2006)).

The Haitian and Chilean Earthquakes

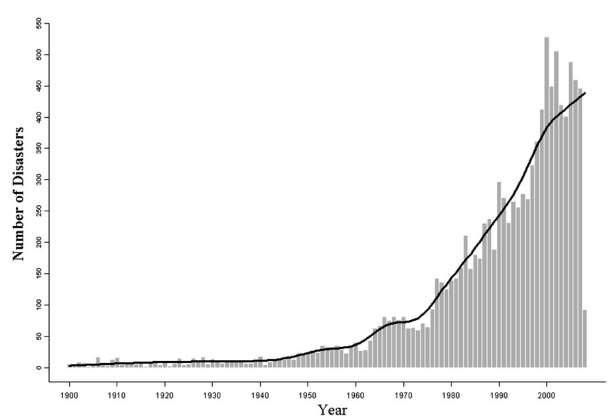
It is a year since the devastating 7.0 earthquake shook Haiti, but on its first anniversary, piles of rubble remain a constant reminder of the destruction caused by the disaster.

According to the UN Development Programme (UNDP), almost 200,000 buildings collapsed in Port-au-Prince and surrounding areas, *creating an estimated 10 million cubic meters of shattered concrete, twisted steel and other debris (the equivalent of 10 World Trade Center sites)*.

To-date, just a fifth of the debris has been cleared, blocking many reconstruction efforts!

Marcel Fortier, head of the International Federation of Red Cross and Red Crescent Societies in Haiti noted *that it would take 200 trucks a total of 11 years to clear all the rubble caused by the earthquake in Haiti.*

Disasters have brought an unprecedented impact on human lives in the 21st century and the number of disasters is growing. From January to October 2005, *an estimated 97,490 people were killed in disasters globally; 88,117 of them because of natural disasters*.



Frequency of disasters [Source: Emergency Events Database (2008)]

The Emergency Events Database (2008) defines a *disaster* as an event that fits at least one of the following criteria:

1). 10 or more people killed;

2). 100 or more people affected;

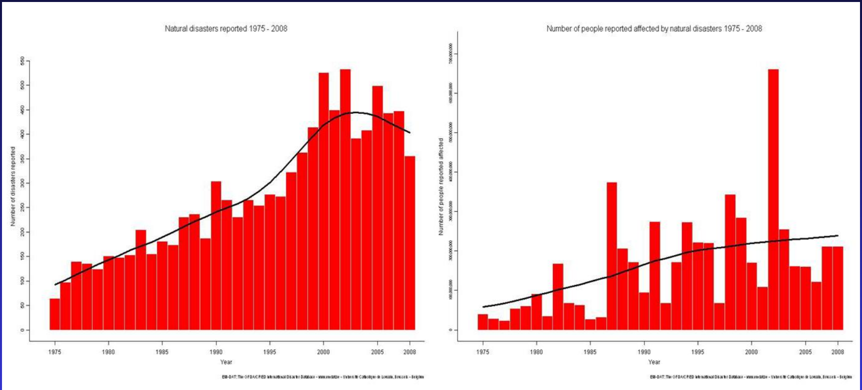
3). declaration of a state of emergency;

4). call for international assistance.

According to the Federal Emergency Management Agency (FEMA) (1992), a catastrophe disaster is *"An event that results in large numbers of deaths and injuries; causes extensive damage or destruction of facilities that provide and sustain human needs; produces an overwhelming demand on state and local response resources and mechanisms; causes a severe long-term effect on general economic activity; and severely affects state, local, and private-sector capabilities to begin and sustain response activities."*

Disasters have a catastrophic effect on human lives and a region's or even a nation's resources.

Natural Disasters (1975–2008)

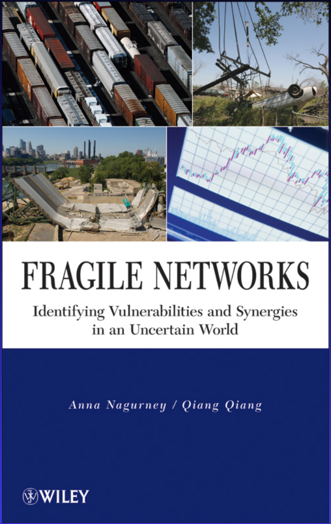


However, although the average number of disasters has been increasing annually over the past decade the average percentage of needs met by different sectors in the period 2000 through 2005 identifies significant shortfalls.

According to Development Initiatives (2006), based on data in the Financial Tracking System of the Office for the Coordination of Humanitarian Affairs, from 2000-2005, the average needs met by different sectors in the case of disasters were:

- 79% by the food sector;
- 37% of the health needs;
- 35% of the water and sanitation needs;
- 28% of the shelter and non-food items, and
- 24% of the economic recovery and infrastructure needs.

Fragile Networks



We are living in a world of *Fragile Networks*.

Transportation networks may be characterized by *decentralized decision-making* as in congested urban transportation associated with the different economic agents or by *centralized* decision-making as in freight networks.

Transportation networks are, in fact, *Complex Network Systems*.

Hence, *any formalism that seeks to model transportation and its resiliency and to provide quantifiable insights and measures must be a system-wide one and network-based.*

Indeed, such crucial issues as the stability and resiliency of transportation, as well as their adaptability and responsiveness to events in *a global environment of increasing risk and uncertainty* can only be rigorously examined from the view of critical transportation infrastructure and its usage as network systems.

Characteristics of Transportation Networks Today

- *large-scale nature* and complexity of network topology;
- *congestion*, which leads to nonlinearities;
- *alternative behavior of users of the networks*, which may lead to paradoxical phenomena;
- *possibly conflicting criteria associated with optimization*;
- *interactions among the underlying networks themselves*, such as the Internet with electric power networks, financial networks, and transportation and logistical networks;
- recognition of *their fragility and vulnerability*;
- policies surrounding networks today may have major impacts not only economically, but also *socially, politically, and security-wise*.

Transportation Network Design Must Capture the Behavior of Users

Behavior on Congested Networks

Decision-makers select their cost-minimizing routes.

		User-Optimized
Decentralized	Selfish	U–O
vs. ⟺	vs. ⟺	vs.
Centralized	Unselfish	S–O
		System-Optimized

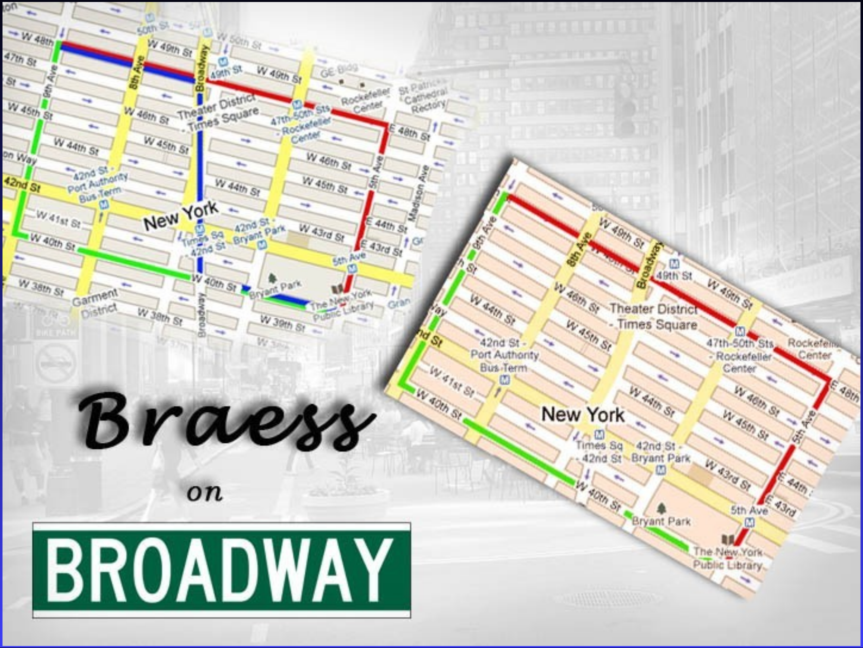
Flows are routed so as to minimize the total cost to society.

The Braess Paradox Around the World

1969 - Stuttgart, Germany - The traffic worsened until a newly built road was closed.

1990 - Earth Day - New York City - 42^{nd} Street was closed and traffic flow improved.

2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.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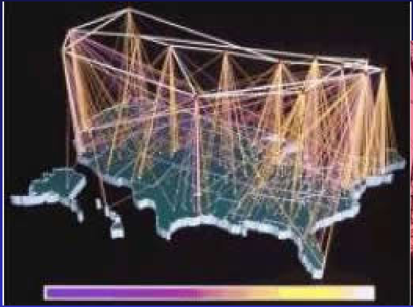
on
BROADWAY
New York
Theater District
- Times Square
Bryant Park
The New York
Public Library
Rockefeller
Center
42nd St -
Port Authority
Bus Term
Times Sq
- 42nd St
42nd St -
Bryant Park
47th-50th Sts
- Rockefeller
Center
W 49th St
W 46th St
W 45th St
W 44th St
W 43rd St
W 41st St
W 40th St
8th Ave
Broadway
5th Ave

Other Critical Infrastructure Networks that Behave like Traffic Networks



The Internet and electric power networks

Some of the Recent Literature on Network Vulnerability

- Latora and Marchiori (2001, 2002, 2004)
- Holme, Kim, Yoon and Han (2002)
- Taylor and Deste (2004)
- Murray-Tuite and Mahmassani (2004)
- Chassin and Posse (2005)
- Barrat, Barthlemy and Vespignani (2005)
- Sheffi (2005)
- DallAsta, Barrat, Barthlemy and Vespignani (2006)
- Jenelius, Petersen and Mattson (2006)
- Taylor and DEste (2007)
- Nagurney and Qiang (2007, 2008, 2009)

Network Centrality Measures

- Barrat et al. (2004, pp. 3748), The identification of the most central nodes in the system is a major issue in network characterization.
- Centrality Measures for Non-Weighted Networks
  - Degree, betweenness (node and edge), closeness (Freeman (1979), Girvan and Newman (2002))
  - Eigenvector centrality (Bonacich (1972))
  - Flow centrality (Freeman, Borgatti and White (1991))
  - Betweenness centrality using flow (Izquierdo and Hanneman (2006))
  - Random-work betweenness, Current-flow betweenness (Newman and Girvan (2004))
- Centrality Measures for Weighted Networks (Very Few)
  - Weighted betweenness centrality (Dall'Asta et al. (2006))
  - Network efficiency measure (Latora-Marchiori (2001))

Which Nodes and Links Really Matter?

The Nagurney and Qiang (N-Q) Network Efficiency / Performance Measure

Definition: A Unified Network Performance Measure

The network performance/efficiency measure, $\mathcal{E}(\mathcal{G}, d)$, for a given network topology $\mathcal{G}$ and the equilibrium (or fixed) demand vector d, is:

$$\mathcal{E} = \mathcal{E}(\mathcal{G}, d) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_W},$$

where recall that n_W is the number of O/D pairs in the network, and d_w and λ_w denote, for simplicity, the equilibrium (or fixed) demand and the equilibrium disutility for O/D pair w, respectively.

The Importance of Nodes and Links

Definition: Importance of a Network Component

The importance of a network component $g \in \mathcal{G}$, $I(g)$, is measured by the relative network efficiency drop after g is removed from the network:

$$I(g) = \frac{\triangle \mathcal{E}}{\mathcal{E}} = \frac{\mathcal{E}(\mathcal{G}, d) - \mathcal{E}(\mathcal{G} - g, d)}{\mathcal{E}(\mathcal{G}, d)}$$

where $\mathcal{G} - g$ is the resulting network after component g is removed from network $\mathcal{G}$.

The Approach to Identifying the Importance of Network Components

The elimination of a link is treated in the N-Q network efficiency measure by removing that link while the removal of a node is managed by removing the links entering and exiting that node.

In the case that the removal results in no path connecting an O/D pair, we simply assign the demand for that O/D pair to an abstract path with a cost of infinity.

The N-Q measure is well-defined even in the case of disconnected networks.

The Advantages of the N-Q Network Efficiency Measure

- The measure captures *demands, flows, costs, and behavior of users*, in addition to network topology.

- The resulting importance definition of network components is applicable and *well-defined even in the case of disconnected networks*.

- It can be used to identify the *importance (and ranking) of either nodes, or links, or both*.

- It can be applied to *assess the efficiency/performance of a wide range of network systems, including financial systems and supply chains under risk and uncertainty*.

- It is applicable also to *elastic demand networks* (Qiang and Nagurney, *Optimization Letters* (2008)).

- It is *applicable to dynamic networks*, *including the Internet*

Some Applications of the N-Q Measure

The Sioux Falls Network

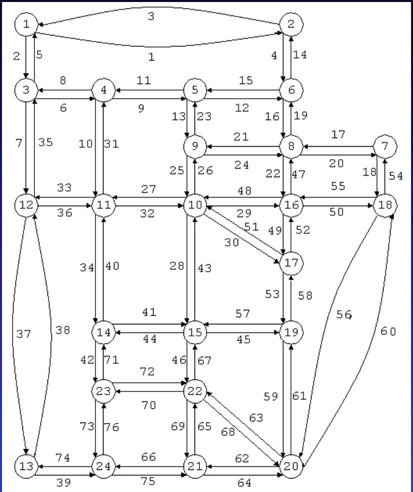


Figure 1: The Sioux Falls network with 24 nodes, 76 links, and 528 O/D pairs of nodes.

Importance of Links in the Sioux Falls Network

The computed network efficiency measure $\mathcal{E}$ for the Sioux Falls network is $\mathcal{E} = 47.6092$. Links 56, 60, 36, and 37 are the most important links, and hence special attention should be paid to protect these links accordingly, while the removal of links 10, 31, 4, and 14 would cause the least efficiency loss.

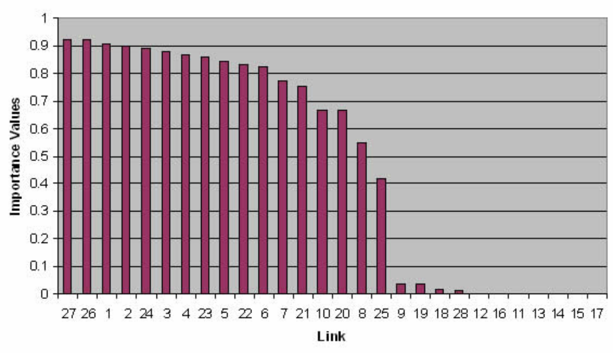


Figure 2: The Sioux Falls network link importance rankings

According to the European Environment Agency (2004), *since 1990, the annual number of extreme weather and climate related events has doubled, in comparison to the previous decade*. These events account for approximately 80% of all economic losses caused by catastrophic events. In the course of climate change, catastrophic events are projected to occur more frequently (see Schulz (2007)).

Schulz (2007) applied *N-Q network efficiency measure to a German highway system in order to identify the critical road elements* and found that this measure provided more reasonable results than the measure of Taylor and DEste (2007).

The N-Q measure can also be used to assess which links should be added to improve efficiency. *This measure was used for the evaluation of the proposed North Dublin (Ireland) Metro system* (October 2009 Issue of *ERCIM News*).

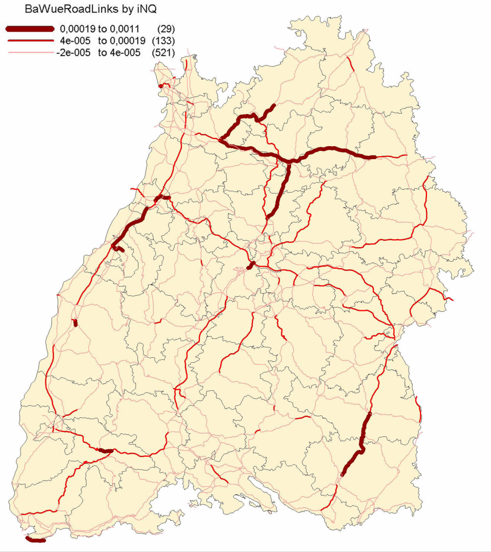


Figure 3: Comparative Importance of the links for the Baden - Wurttemberg Network – Modelling and analysis of transportation networks in earthquake prone areas via the N-Q measure, Tyagunov et al.

What About Transportation Network Robustness?

The concept of *system robustness* has been studied in engineering and computer science. IEEE (1990) defined robustness as *"the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions."*

Gribble (2001) defined system robustness as *"the ability of a system to continue to operate correctly across a wide range of operational conditions, and to fail gracefully outside of that range."*

Ali et al. (2003) considered an allocation mapping to be robust if it *"guarantees the maintenance of certain desired system characteristics despite fluctuations in the behavior of its component parts or its environment."*

Schillo et al. (2001) argued that robustness has to be studied *"in relation to some definition of performance measure."*

Holmgren (2007) stated: *"Robustness signifies that the system will retain its system structure (function) intact (remain unchanged or nearly unchanged) when exposed to perturbations."*

Definition: Network Robustness Measure Under User-Optimizing Decision-Making Behavior

The robustness measure $\mathcal{R}^\gamma$ for a network $\mathcal{G}$ with the vector of user link cost functions c, the vector of link capacities u, the vector of demands d (either fixed or elastic) is defined as the relative performance retained under a given uniform capacity retention ratio γ with $\gamma \in (0, 1]$ so that the new capacities are given by γu. Its mathematical definition is

$$\mathcal{R}^\gamma = \mathcal{R}(\mathcal{G}, c, \gamma, u) = \frac{\mathcal{E}^\gamma}{\mathcal{E}} \times 100\%$$

where $\mathcal{E}$ and $\mathcal{E}^\gamma$ are the network performance measures with the original capacities and the remaining capacities, respectively.

For example, if $\gamma = .8$, this means that the user link cost functions now have the link capacities given by $.8u_a$ for all links $a \in \mathcal{L}$; if $\gamma = .4$, then the link capacities become $.4u_a$ for all links $a \in \mathcal{L}$, and so on.

According to this Definition, *a network under a given level of capacity retention or deterioration is considered to be robust if the network performance stays close to the original level*.

We can also study network robustness from *the perspective of network capacity enhancement*.

Such an analysis *provides insights into link investments*. In this case $\gamma \geq 1$ and, for definiteness (and as suggested in Nagurney and Qiang (2009)), we refer to the network robustness measure in this context as the *"capacity increment ration."*

An Application to the Anaheim Network

Each link of the Anaheim network has a link travel cost functional form of the BPR form. There are 461 nodes, 914 links, and 1,406 O/D pairs in the Anaheim network.

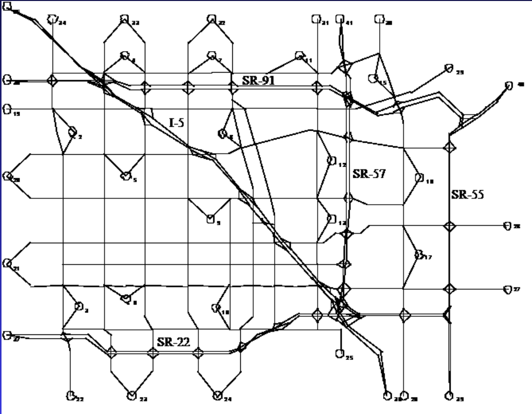


Figure 4: The Anaheim network

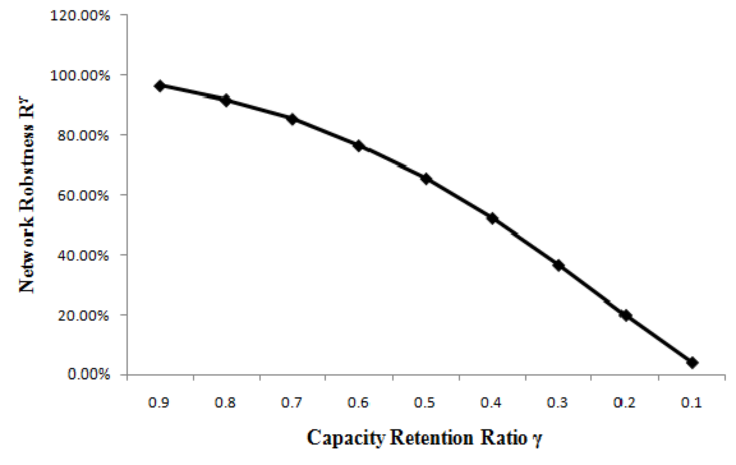


Figure 5: Robustness vs. Capacity Retention Ratio for the Anaheim Network

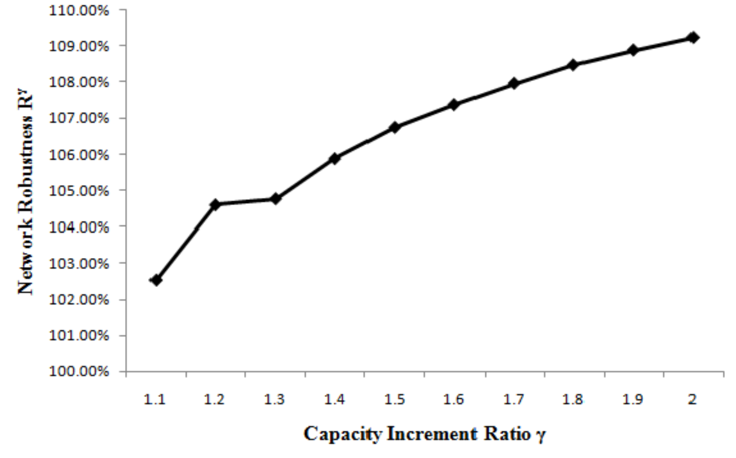


Figure 6: Robustness vs. Capacity Increment Ratio for the Anaheim Network

Different Perspectives on Transportation Network Robustness

Relative Total Cost Indices

The definition of the index under the user-optimizing flow pattern, denoted by $\mathcal{I}^{\gamma}_{U-O}$:

$$\mathcal{I}^{\gamma}_{U-O} = \mathcal{I}_{U-O}(\mathcal{G}, c, d, \gamma, u) = \frac{TC^{\gamma}_{U-O} - TC_{U-O}}{TC_{U-O}} \times 100\%,$$

where TC_{U-O} and TC^{γ}_{U-O} are the total network costs evaluated under the U-O flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

The definition of the index under the system-optimizing flow pattern is:

$$\mathcal{I}^{\gamma}_{S-O} = \mathcal{I}_{S-O}(\mathcal{G}, c, d, \gamma, u) = \frac{TC^{\gamma}_{S-O} - TC_{S-O}}{TC_{S-O}} \times 100\%,$$

where TC_{S-O} and TC^{γ}_{S-O} are the total network costs evaluated at the S-O flow pattern with the capacities as above.

From these definitions, a network, under a given capacity retention/deterioration ratio γ (and either S-O or U-O behavior) is *considered to be robust if the index $\mathcal{I}^\gamma$ is low.*

This means that the relative total cost does not change much; hence the network may be viewed as being more robust than if the relative total cost were large.

We can also study the relative total cost improvement after capacity enhancement. In that case, because the relative total cost savings need to be computed, we reverse the order of subtraction in the previous expressions with $\gamma \geq 1$. Furthermore, γ is defined as the "capacity increment ratio."

Therefore, the larger the relative total cost index is, the greater the expected total cost savings for a capacity enhancement plan for a specific γ.

Relationship to the Price of Anarchy

The *price of anarchy*, $\mathcal{P}$, defined as

$$\mathcal{P} = \frac{TC_{U-O}}{TC_{S-O}},$$

captures the relationship between total costs *across* distinct behavioral principles, whereas the above indices are focused on the degradation of network performance *within* U-O or S-O behavior.

The relationship between the ratio of the two indices and the price of anarchy

$$\frac{I^{\gamma}_{S-O}}{I^{\gamma}_{U-O}} = \frac{[TC^{\gamma}_{S-O} - TC_{S-O}]}{[TC^{\gamma}_{U-O} - TC_{U-O}]} \times \mathcal{P}.$$

The term preceding the price of anarchy may be less than 1, greater than 1, or equal to 1, depending on the network and data.

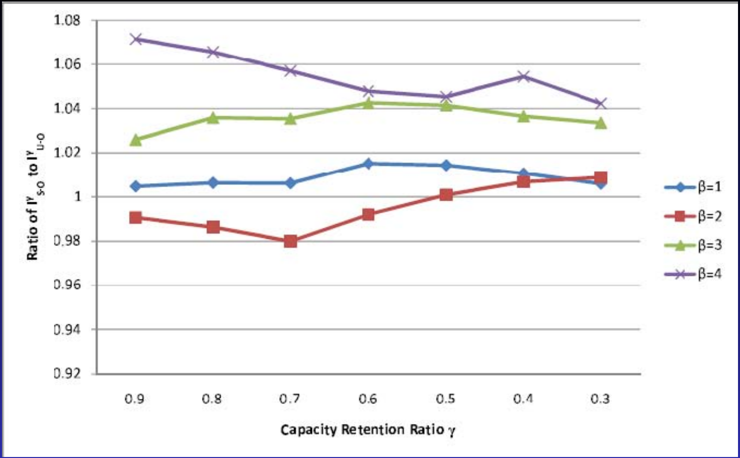


Figure 7: Example: The Sioux Falls network

This network is always more robust under U-O behavior except when β is equal to 2 (where β is the power to which the link flow is raised to into the BPR function) and $\gamma \in [0.5, 0.9]$.

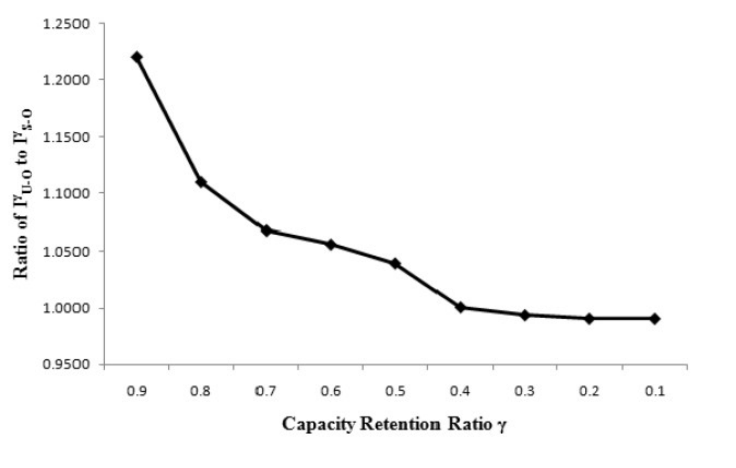


Figure 8: Example: The Anaheim network

This network is more robust under the S-O solution when the capacity retention ratio γ is above .3.

Which Nodes and Links Matter Environmentally?

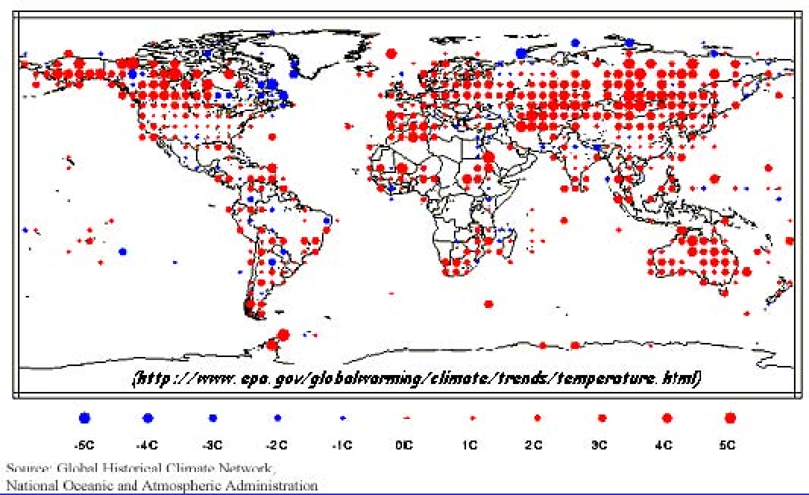


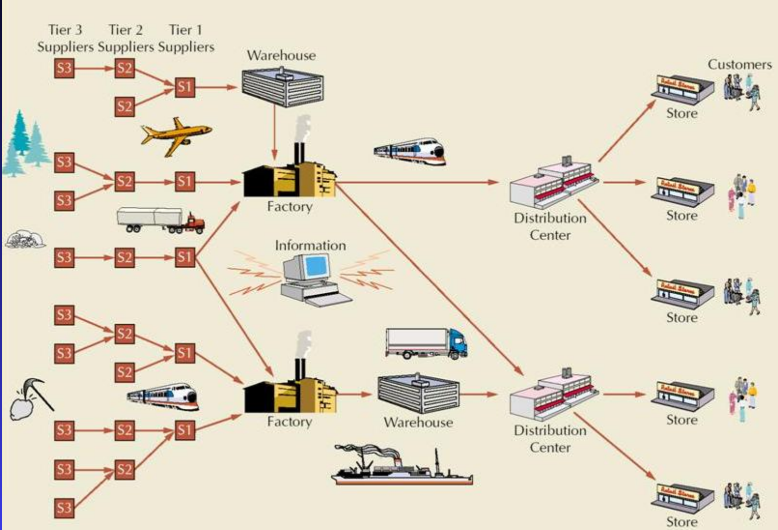
Figure 9: Global Annual Mean Temperature Trend 1950–1999

Figure 10: Impacts of climate change on transportation infrastructure

We have also extended our measures to construct environmental impact assessment indices and environmental link importance identifiers under either U-O or S-O behaviors.

What About Transportation's Role in Disaster Relief?

A General Supply Chain



Haiti Earthquake in 2010

Delivering the humanitarian relief supplies (water, food, medicines, etc.) to the victims was a major logistical challenge.

Humanitarian Relief

In 2001 the total U.S. expenditure for humanitarian economic assistance was $1.46B, of which 9.7% represents a special supplement for victims of floods and typhoons in southern Africa (Tarnoff and Nowels (2001)).

The period between 2000-2004 experienced an average annual number of disasters that was 55% higher than the period of 1995-1999 with 33% more people affected in the more recent period (Balcik and Beamon (2008)).

According to ISDR (2006) 157 million people required immediate assistance due to disasters in 2005 with approximately 150 million requiring asistance the year prior (Balcik and Beamon (2008)).

Humanitarian Supply Chains

The supply chain is a critical component not only of corporations but also of humanitarian organizations and their logistical operations.

At least 50 cents of each dollars worth of food aid is spent on transport, storage and administrative costs (Dugger (2005)).

Vulnerability of Humanitarian Supply Chains

Extremely poor logistic infrastructures: Modes of transportation include trucks, barges, donkeys in Afghanistan, and elephants in Cambodia (Shister (2004)).

To ship the humanitarian goods to the affected area in the first 72 hours after disasters is crucial. The successful execution is not just a question of money but a difference between life and death (Van Wassenhove (2006)).

Corporations expertise with logistics could help public response efforts for nonprofit organizations (Sheffi (2002), Samii et al.(2002)).

In the humanitarian sector, organizations are 15 to 20 years behind, as compared to the commercial arena, regarding supply chain network development (Van Wassenhove (2006)).

It is clear that better-designed supply chain networks in which transportation plays a pivotal role would have facilitated and enhanced various emergency preparedness and relief efforts and would have resulted in less suffering and lives lost.

Critical Needs Products

Critical needs products are those that are *essential to the survival of the population*, and can include, for example, vaccines, medicine, food, water, etc., depending upon the particular application.

The demand for the product should be met as nearly as possible since otherwise there may be additional loss of life.

In times of crises, a *system-optimization* approach is mandated since the demands for critical supplies should be met (as nearly as possible) at minimal total cost.

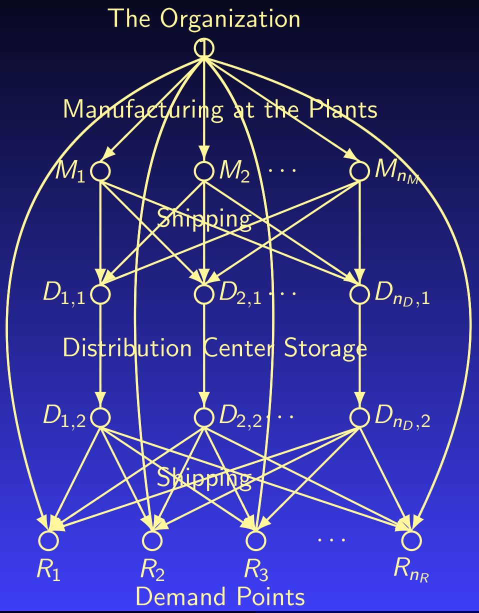
We have now developed a framework for the optimal design of critical needs product supply chains:

"Supply Chain Network Design for Critical Needs with Outsourcing,"

A. Nagurney, M. Yu, and Q. Qiang, *Papers in Regional Science*, in press,

where additional background as well as references can be found.

Supply Chain Network Topology with Outsourcing

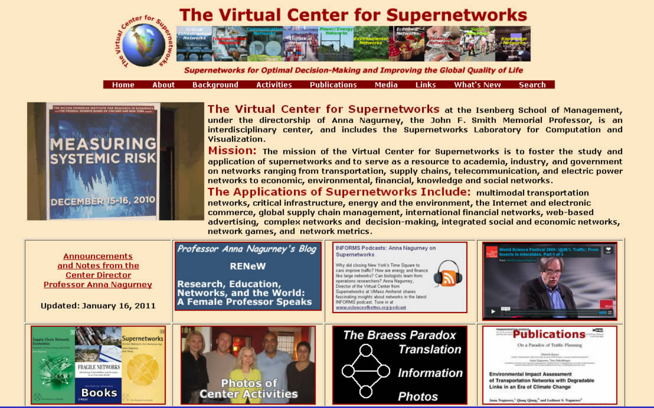


Our recent research includes aspects of design for robustness and resiliency.

- "Modeling of Supply Chain Risk Under Disruptions with Performance Measurement and Robustness Analysis," Q. Qiang, A. Nagurney, and J. Dong (2009), in *Managing Supply Chain Risk and Vulnerability: Tools and Methods for Supply Chain Decision Makers*, T. Wu and J. Blackhurst, Editors, Springer, London, England, 91-111.

- "A Bi-Criteria Measure to Assess Supply Chain Network Performance for Critical Needs Under Capacity and Demand Disruptions," Q. Qiang and A. Nagurney (2010).

THANK YOU!



For more information, see: http://supernet.som.umass.edu