Fragile Networks: Identifying Vulnerabilities and Synergies in an Uncertain World

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Pre-Conference Tutorial – Module II

Outline of Tutorial

- Module I: Network Fundamentals, Efficiency Measurement, and Vulnerability Analysis

- Module II: Applications and Extensions

- ModuIe III: Mergers and Acquisitions, Network Integration, and Synergies

Robustness in Engineering and Computer Science

IEEE (1990) defined robustness as *the degree to which a system of 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*.

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

Motivation for Research on Transportation Network Robustness

According to the American Society of Civil Engineering:

Poor maintenance, natural disasters, deterioration over time, as well as unforeseen attacks now lead to estimates of *$94 billion in the US* in terms of needed repairs for roads alone.

Poor road conditions in the United States cost US motorists *$54 billion in repairs and operating costs annually*.

Transportation Network Robustness

The focus of the robustness of networks (and complex networks) has been on the impact of different network measures when facing the removal of nodes on networks.

We focus on the *degradation of links through reductions in their capacities* and the effects on the induced travel costs in the presence of known travel demands and different functional forms for the links.

"Robustness" in Transportation

Sakakibara et al. (2004) proposed a topological index. The authors considered a transportation network to be robust if it is "dispersed" in terms of the number of links connected to each node.

Scott et al. (2005) examined transportation network robustness by analyzing the increase in the total network cost after removal of certain network components.

A New Approach to Transportation Network Robustness

The Importance of Studying Transportation Network Robustness

The US is experiencing a *freight capacity crisis* that threatens the strength and productivity of the US economy. According to the American Road & Transportation Builders Association (see Jeanneret (2006)), nearly 75% of US freight is carried in the US on highways, and bottlenecks are causing truckers *243 million hours* of delay annually with an estimated associated cost of *$8 billion*.

The number of motor vehicles in the US has risen by *157 million* (or 212.16%) since 1960 while the population of licensed drivers grew by 109 million (or 125.28%) (US Department of Transportation (2004)).

The Transportation Network Robustness Measure

Nagurney and Qiang, Europhysics Letters, 80, December (2007)

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

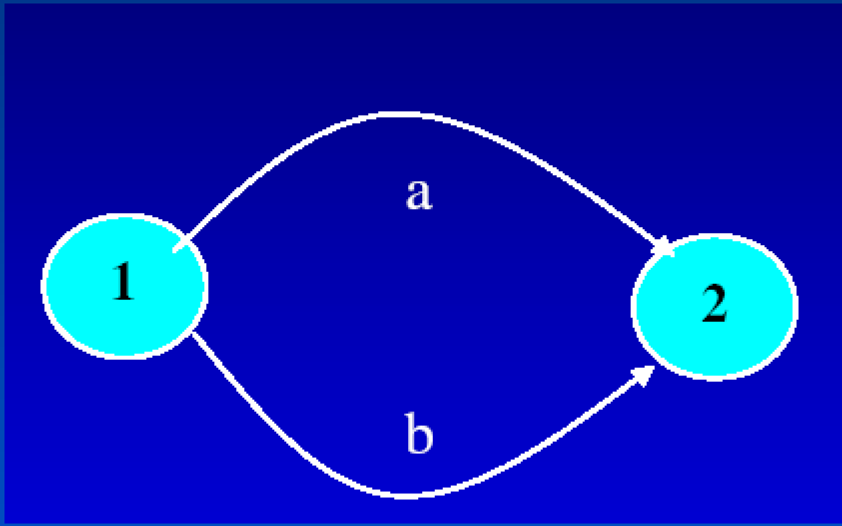
$$\mathcal{R}^\gamma = \mathcal{R}(G, c, d, \gamma, u) = \frac{\mathcal{E}^\gamma}{\mathcal{E}} \times 100\%$$

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

We utilize BPR functions user link cost functions c for the robustness analysis.

A Simple Example

Assume a network with one O/D pair: w_1=(1,2) with demand given by d_{w1}=10.



The paths are: p_1=a and p_2=b.

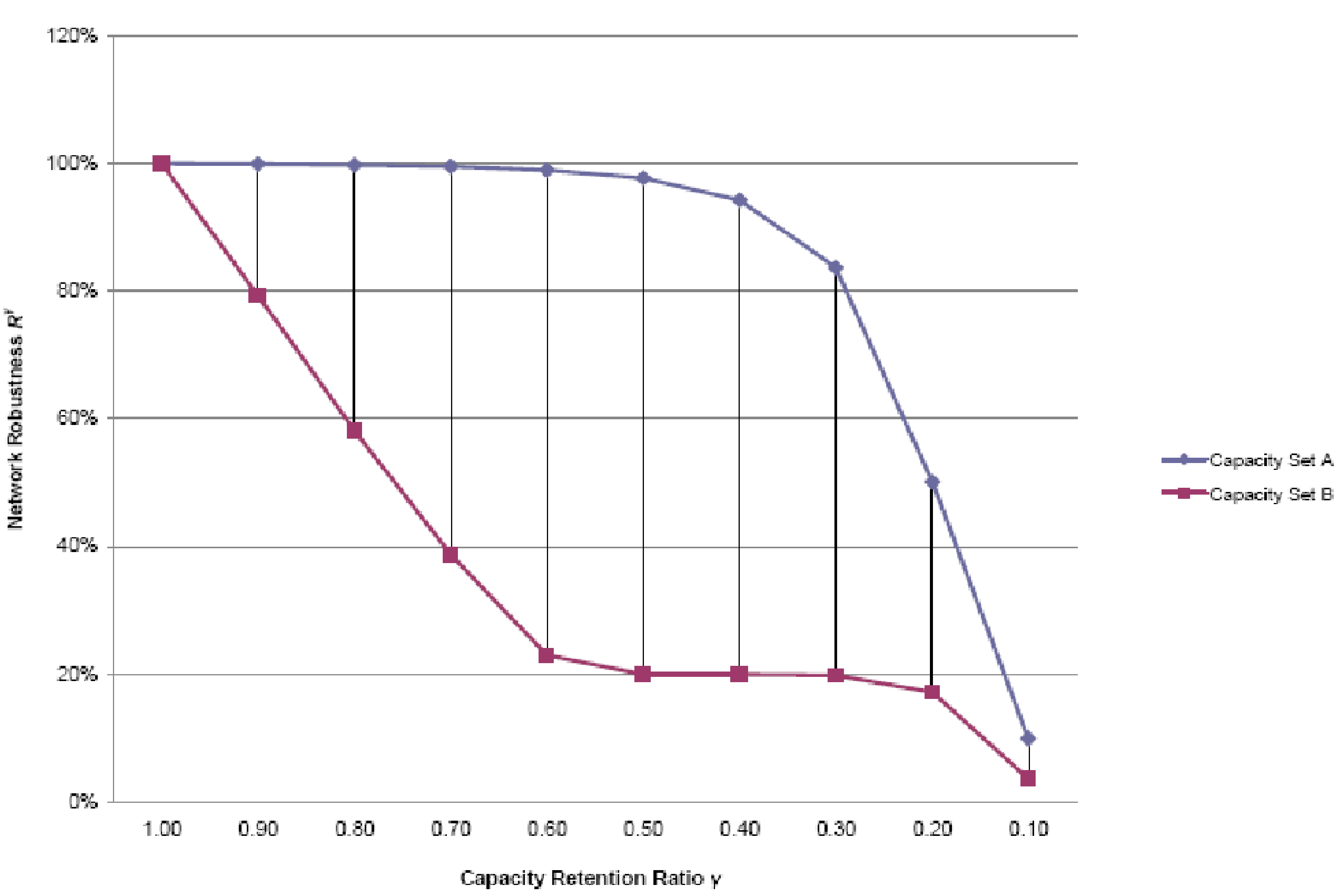
In the BPR link cost function, k=1 and β=4; c_a^0=10 and c_a^0=1.

Assume that there are two sets of capacities:

Capacity Set A, where u_a=u_b=50;

Capacity Set B, where u_a=50 and u_b=10.

Robustness of the Simple Network



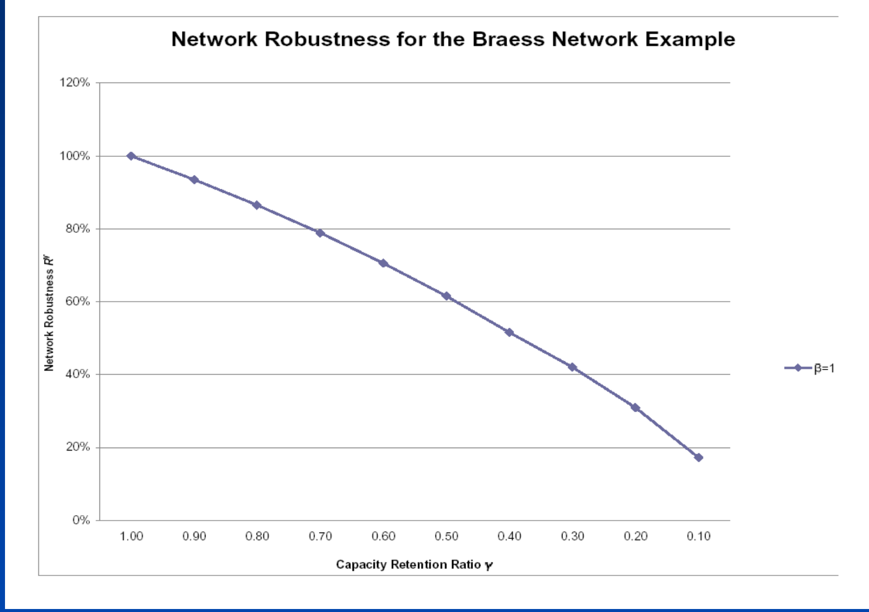
Another Example: Braess Network with BPR Functions

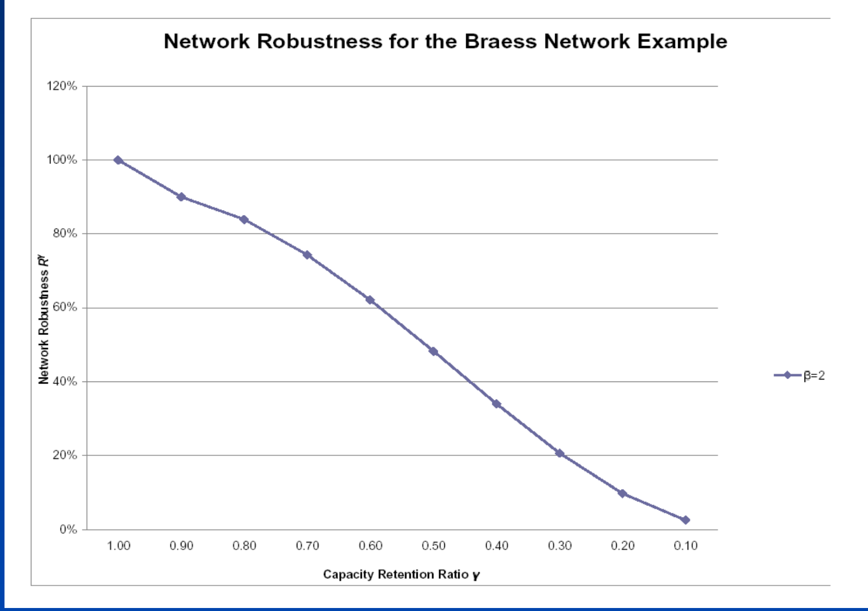
Instead of using the original cost functions, we construct a set of BPR functions as below under which the Braess Paradox still occurs. The new demand is 110.

$$c_a(f_a) = 1 + (\frac{f_a}{20})^\beta, \quad c_b(f_b) = 50(1 + (\frac{f_b}{50})^\beta),$$

$$c_c(f_c) = 50(1 + (\frac{f_b}{50})^\beta), \quad c_d(f_d) = 1 + (\frac{f_d}{20})^\beta,$$

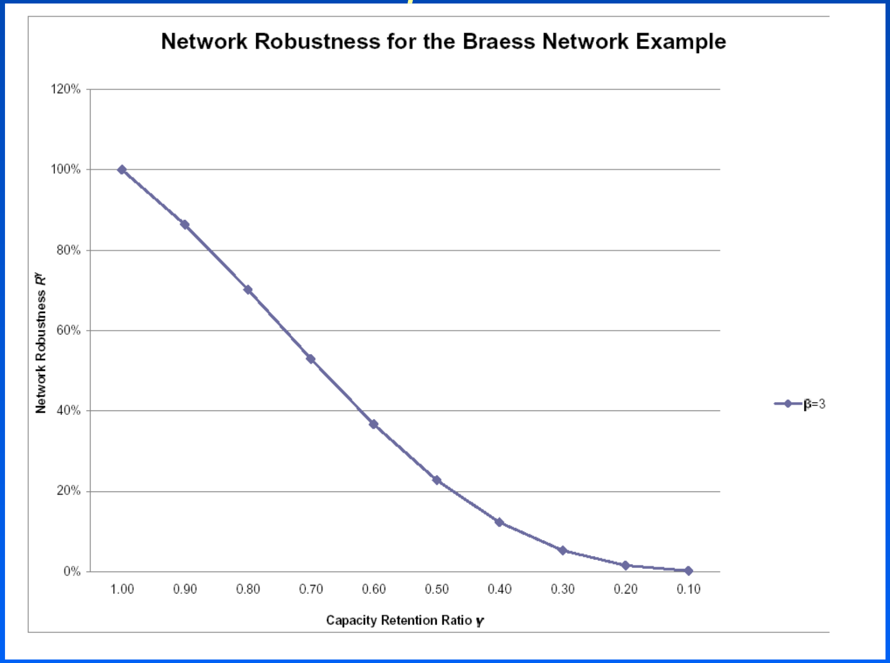
$$c_e(f_e) = 10(1 + (\frac{f_e}{100})^\beta).$$

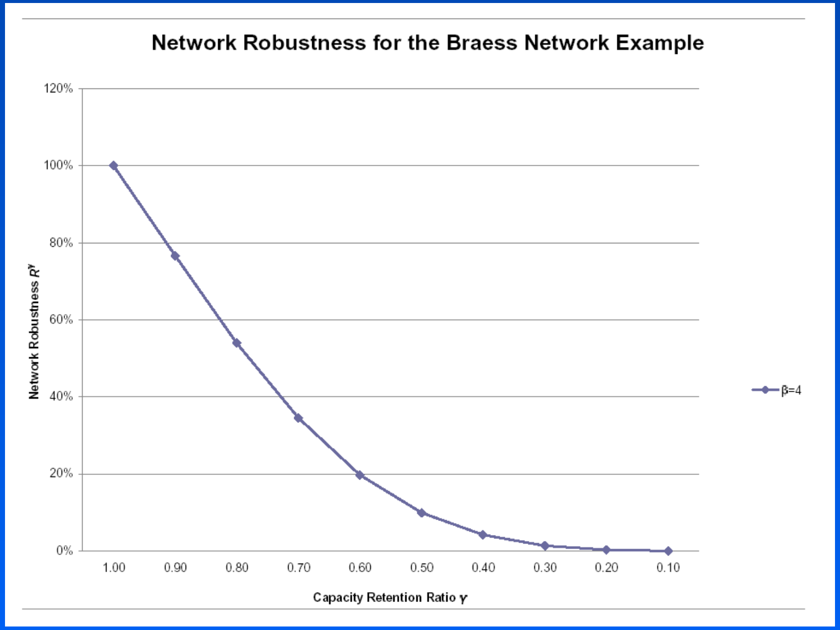




$\beta = 1$

$\beta = 2$



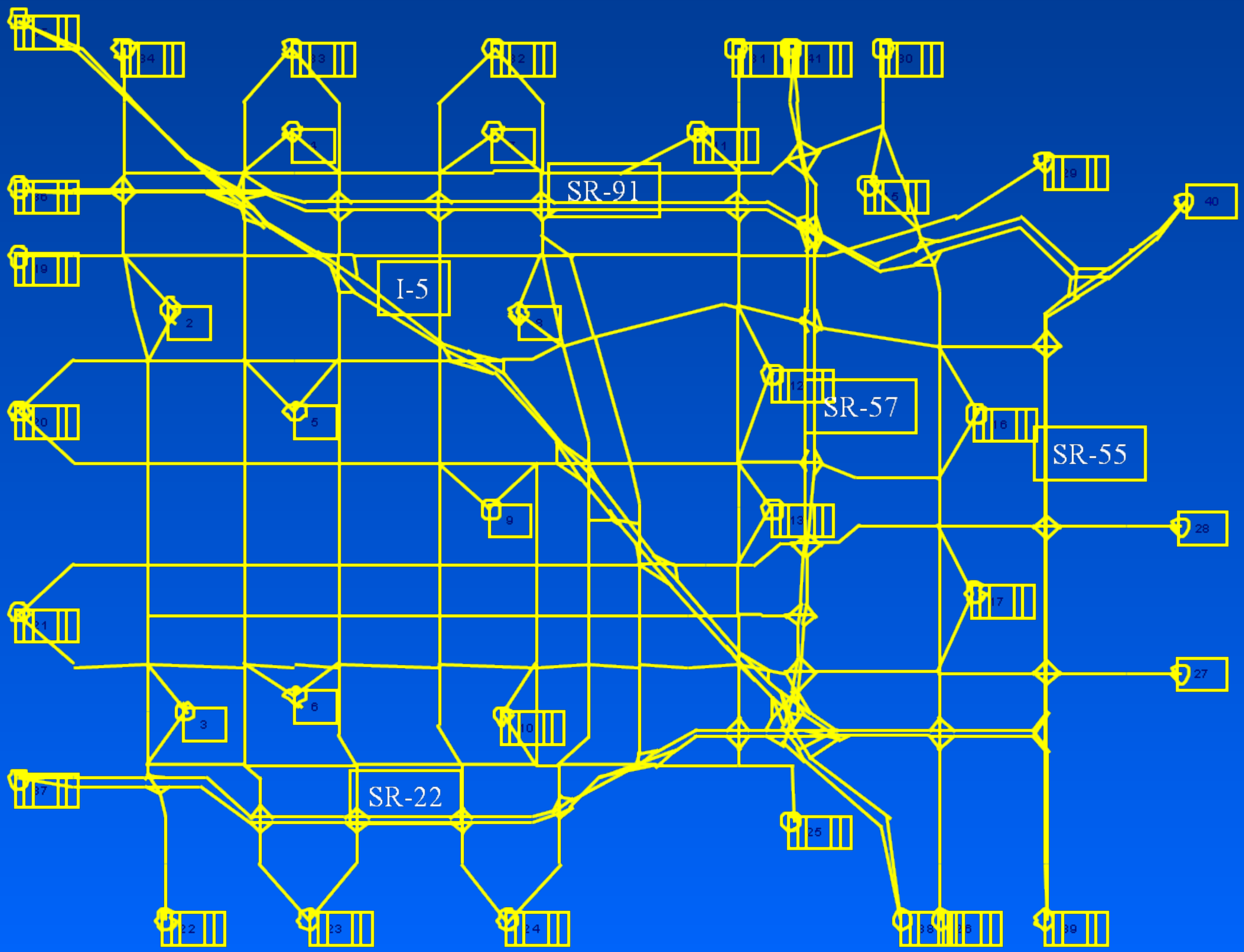


$\beta = 3$

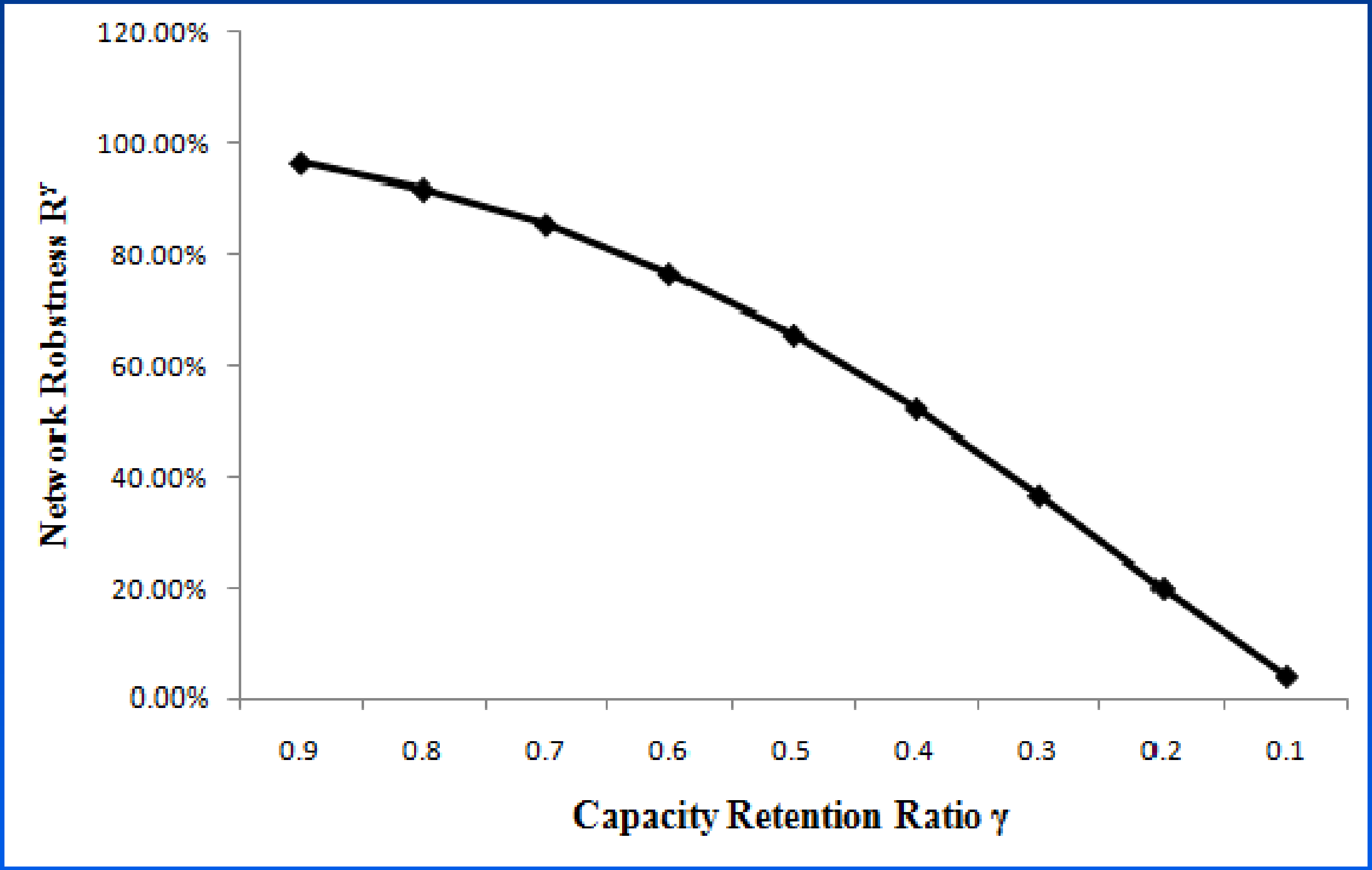
$\beta = 4$

Example: The Anaheim, California Network

There are 461 nodes, 914 links, and 1, 406 O/D pairs in the Anaheim network.



Robustness vs. Capacity Retention Ratio for the Anaheim Network



Different Perspectives on Transportation Network Robustness: Relative Total Cost Indices

- The index is based on the two behavioral solution concepts, namely, the total cost evaluated under the U-O flow pattern, denoted by TC_{U-O}, and the S-O flow pattern, denoted by TC_{S-O}, respectively.

- The relative total cost index for a transportation network *G* with the vector of demands *d*, the vector of user link cost functions *c*, and the vector of link capacities *u* is defined as the relative total cost increase under a given uniform capacity retention ratio γ ($\gamma \in (0, 1]$) so that the new capacities are given by γu. Let *c* denote the vector of BPR user link cost functions and let *d* denote the vector of O/D pair travel demands.

We still utilize BPR functions user link cost functions c for the robustness analysis.

Definition of The Relative Total Cost Indices

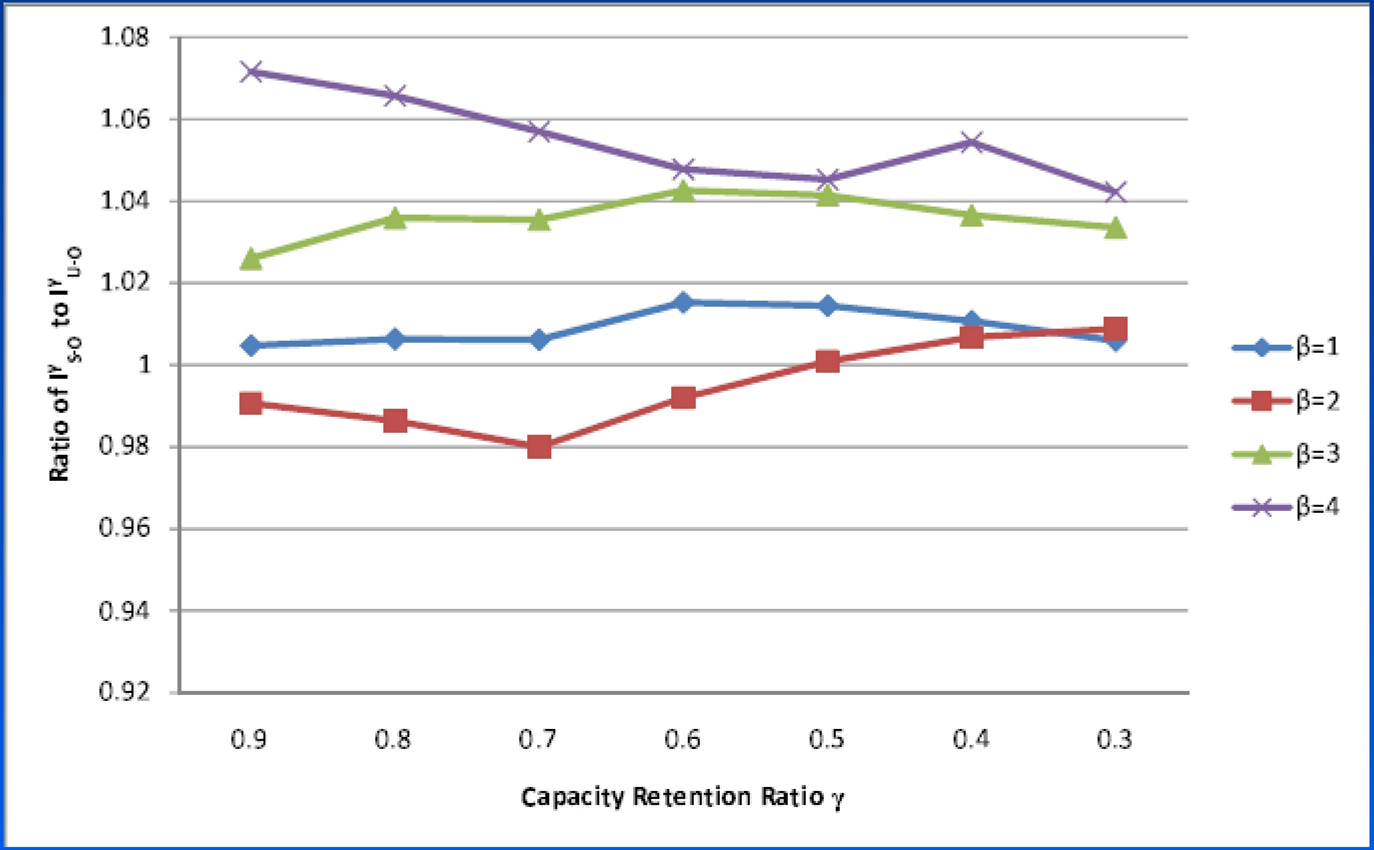
$$\mathcal{I}^{\gamma}_{U-O} = \mathcal{I}_{U-O}(G, c, d, \gamma, u) = \frac{TC^{\gamma}_{U-O} - TC_{U-O}}{TC_{U-O}} \times 100\%,$$

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

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

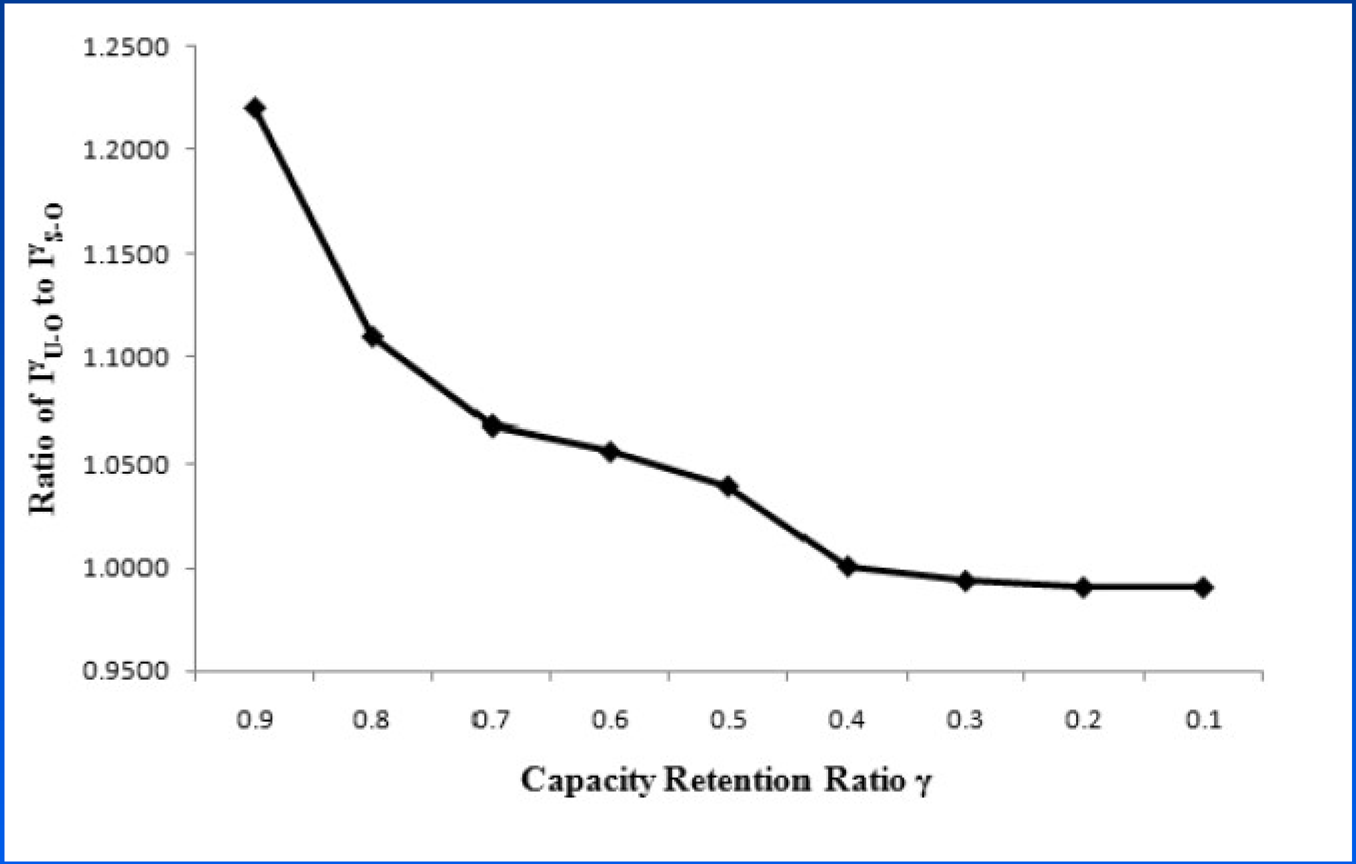
where $TC_{S\text{-}O}$ and $TC^{\gamma}_{S\text{-}O}$ are the total network costs evaluated under the S-O flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

Example: The Sioux Falls Network



From the above figure, we can see that the Sioux-Falls network is always more robust under U-O behavior except when β is equal to 2 and the capacity retention ratio is between 0.5 and 0.9.

Example: The Anaheim Network

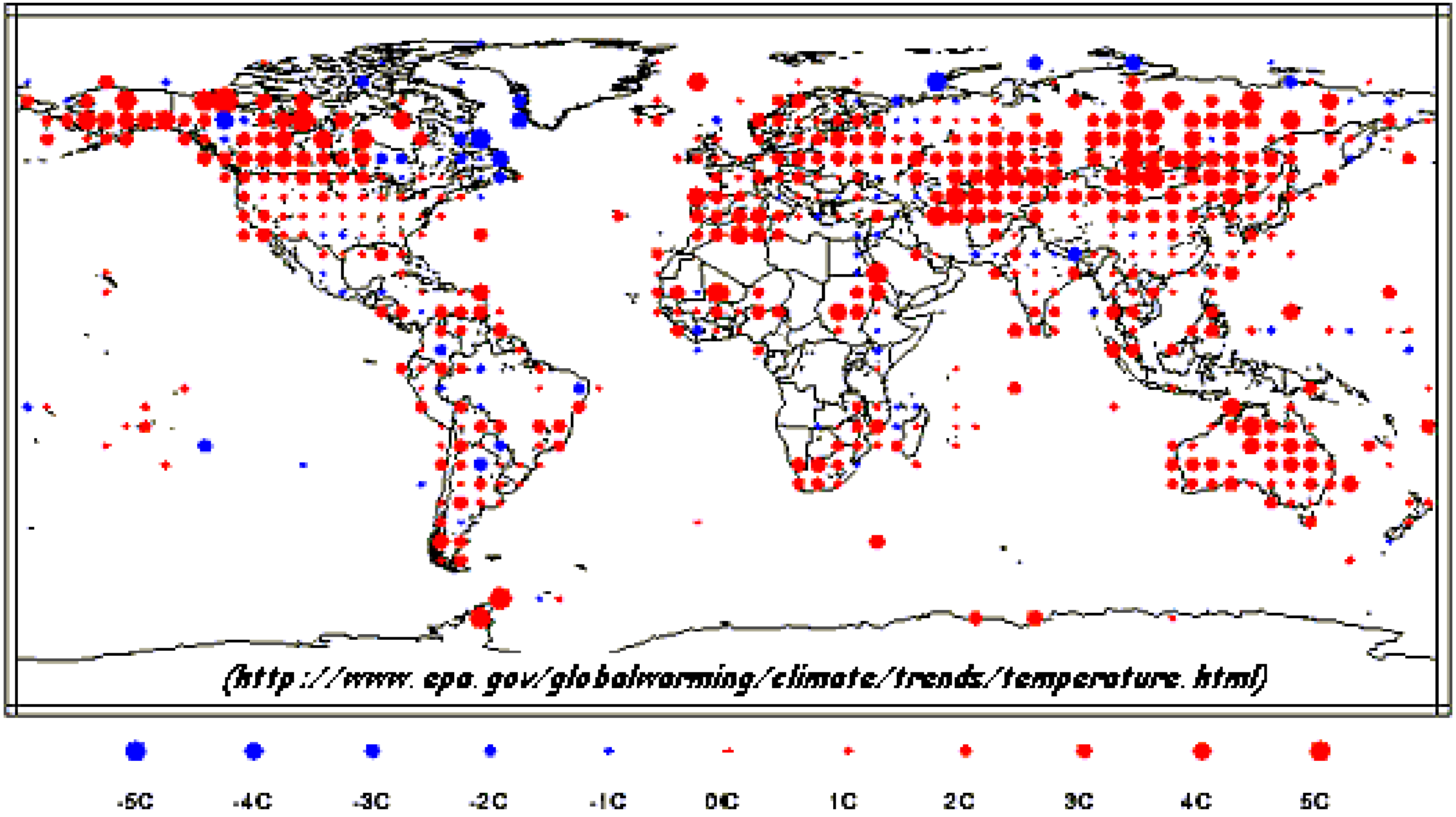


Ratio of $I_{U\text{–}O}$ to $I_{S\text{–}O}$ for the Anaheim Network under the Capacity Retention Ratio γ

Which Nodes and Links Really Matter Environmentally?

If a Transportation Network is Robust According to the Previous Measure, is it True that it is also Environmentally Robust?

Global Annual Mean Temperature Trend 1950-1999



Source: Global Historical Climate Network,
National Oceanic and Atmospheric Administration

Impacts of Climate Change on Transportation Infrastructure



Examples from Alaska (Smith and Lavasseur)

Melting Ground and Sea Ice Destroying Villages in Alaska

Source: globalwarming.house.gov

The Environmental Impact of Transportation Network Degradation

According to an EPA (2006) report, the transportation sector in 2003 accounted for 27% of the total greenhouse gas emissions in the U.S. and the increase in this sector was the largest of any in the period 1990 – 2003.

Knudsen and Bang (2007) claim that infrastructure capacity increases are directly linked to decreases in polluting emissions from motor vehicles. Using a traffic micro-simulation, they showed that upgrading narrow, winding roads or adding a lane to a congested motorway can yield decreases of up to 38% in CO_2 emissions, 67% in CO emissions and 75% in NOx emissions, without generating substantially more car trips .

- The link and node importance identification approach introduced previously does not apply directly to environmental impact assessment.
- We need an approach that can handle both U-O and S-O behaviors.
- The approach should capture the impact of alternative behaviors on the environment as the transportation network is subject to link capacity degradations.

Emission Functions for Transportation Networks

CO Link Emission Function (Yin and Lawphongpanich (2006))

$$e_a(f_a) = 0.2038 \times c_a(f_a) \times e^{0.7962 \times (\frac{l_a}{c_a(f_a)})},$$

where l_a denotes the length of link a and c_a corresponds to the travel time (in minutes) to traverse link a. The length l_a is measured in kilometers for each link $a \in L$ and the emissions are in grams per hour.

Total Emissions on a Link

The expression for total emissions on a link a, denoted by $\hat{e}_a(f_a)$, is given by:

$$\hat{e}_a(f_a) = e_a(f_a) \times f_a.$$

The Total Emissions of CO, TE, Generated on a Network

$$\mathrm{TE} = \sum_{a \in L} \hat{e}_a(f_a).$$

The Environmental Impact Assessment Index

Environmental Impact Assessment Index under the U-O Flow Pattern

$$\mathrm{EI}_{U-O}^{\gamma} = \mathrm{EI}_{U-O}(G, c, d, \gamma, u) = \frac{\mathrm{TE}_{U-O}^{\gamma} - \mathrm{TE}_{U-O}}{\mathrm{TE}_{U-O}},$$

where TE_{U-O} and $\mathrm{TE}_{U-O}^{\gamma}$ are the total emissions generated under the U-O flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

Environmental Impact Assessment Index under the S-O Flow Pattern

$$\mathrm{EI}_{S-O}^{\gamma} = \mathrm{EI}_{S-O}(G, c, d, \gamma, u) = \frac{\mathrm{TE}_{S-O}^{\gamma} - \mathrm{TE}_{S-O}}{\mathrm{TE}_{S-O}},$$

where TE_{S-O} and $\mathrm{TE}_{S-O}^{\gamma}$ are the total emissions generated at the S-O flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

The Environmental Importance Identification for Links

$$\mathrm{I}^{l}_{U-O} = \frac{\mathrm{TE}_{U-O}(G-l) - \mathrm{TE}_{U-O}}{\mathrm{TE}_{U-O}},$$

$$\mathrm{I}^{l}_{S-O} = \frac{\mathrm{TE}_{S-O}(G-l) - \mathrm{TE}_{S-O}}{\mathrm{TE}_{S-O}},$$

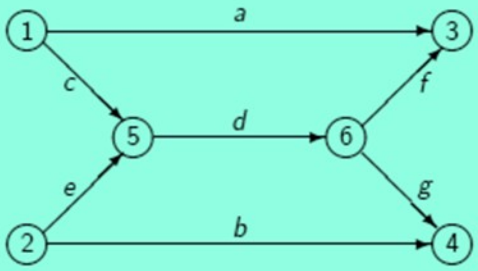
where I^{l}_{U-O} denotes the importance indicator for link l assuming U-O behavior and I^{l}_{S-O} denotes the analogue under S-O behavior; $\mathrm{TE}_{U-O}(G-l)$ denotes the total emissions generated under U-O behavior if link l is removed from the network and $\mathrm{TE}_{S-O}(G-l)$ denotes the same but under S-O behavior.

Example *(Data from Yin anLawphongpanich (2006))*

The network topology is in the figure on the right.
There are two O/D pairs in the network: $w_1 = (1, 3)$ and $w_2 = (2, 4)$ with demands of $d_{w_1} = 3000$ vehicles per hour and $d_{w_2} = 3000$ vehicles per hour. The user link cost functions, which here correspond to travel time in minutes, are as follows:

$c_a(f_a) = 8(1 + .15(\frac{f_a}{2000})^4)$, $c_b(f_b) = 9(1 + .15(\frac{f_b}{2000})^4)$,
$c_c(f_c) = 2(1 + .15(\frac{f_c}{2000})^4)$, $c_d(f_d) = 6(1 + .15(\frac{f_d}{4000})^4)$,
$c_e(f_e) = 3(1 + .15(\frac{f_e}{2000})^4)$, $c_f(f_f) = 3(1 + .15(\frac{f_f}{2500})^4)$,
$c_g(f_g) = 4(1 + .15(\frac{f_g}{2500})^4)$.

The lengths of the links, in kilometers, in turn, which are needed to compute the environmental emissions, are given by: $l_a = 8.0$, $l_b = 9.0$, $l_c = 2.0$, $l_d = 6.0$, $l_e = 3.0$, $l_f = 3.0$, $l_g = 4.0$.



The Environmental Impact Indices Under U-O and S-O Behaviors

Figure: Ratio of TE^{γ}_{U-O} to $TE^{\gamma}{}_{S-O}$ for the Yin and Lawphongpanich (2006) Network

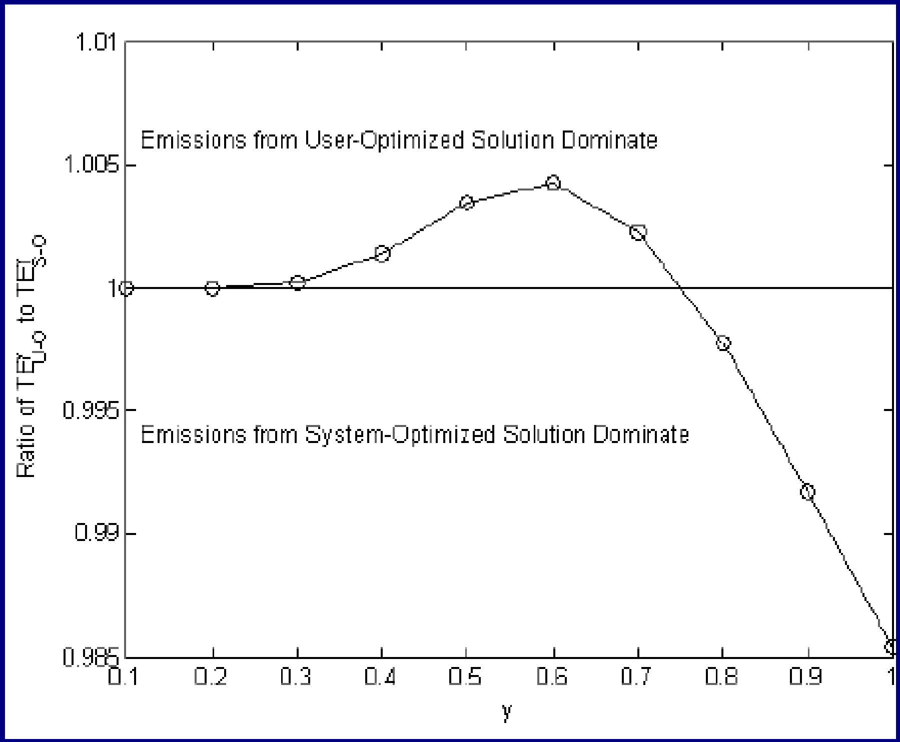
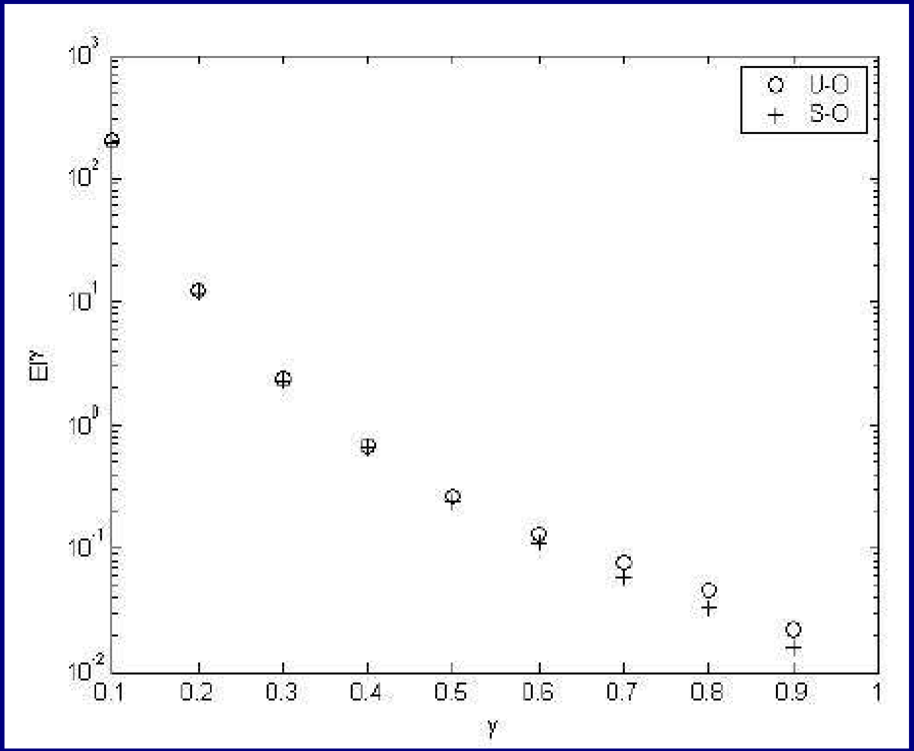
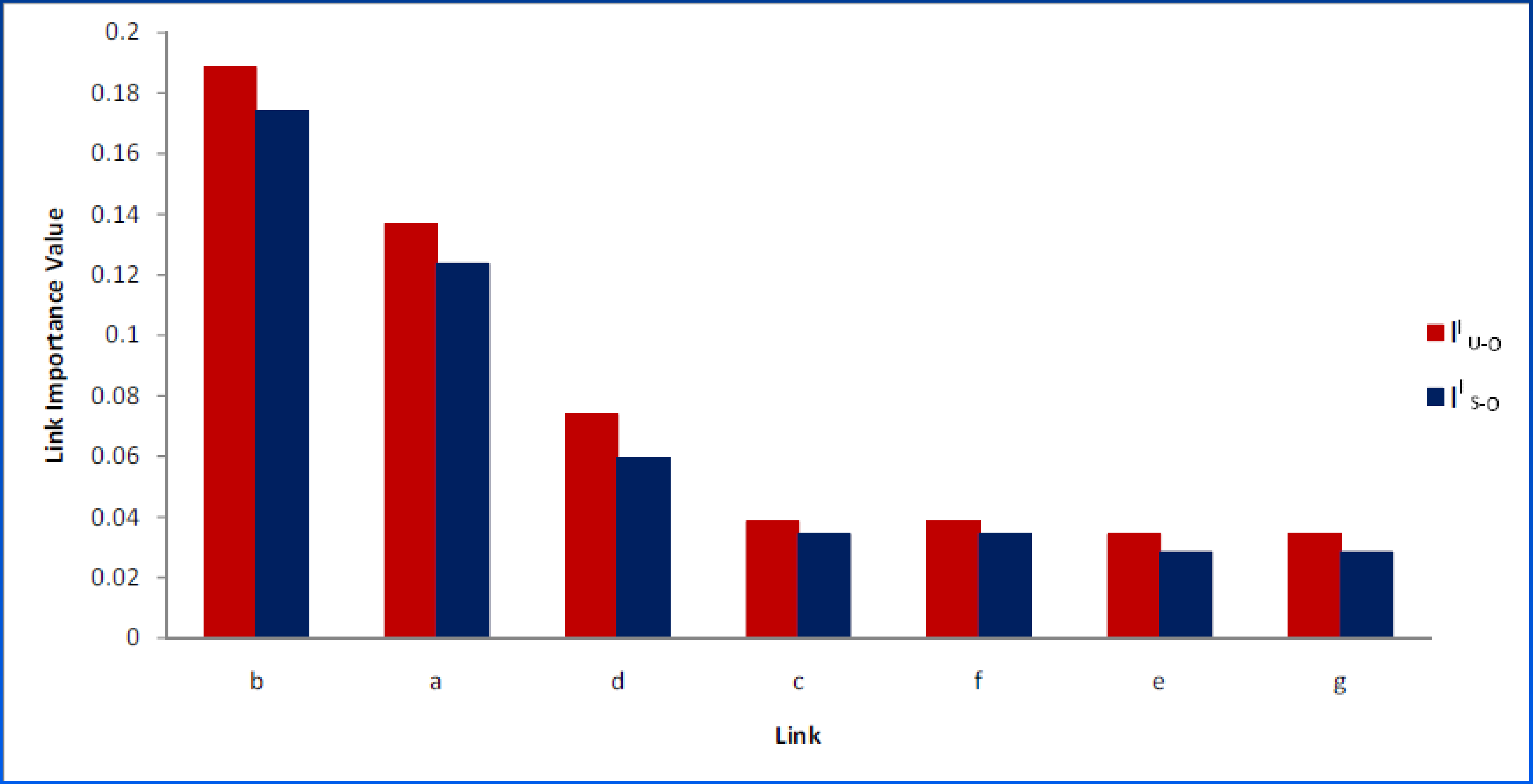


Figure: Plot of EI^{γ}_{U-O} and EI^{γ}_{S-O} for the Yin and Lawphongpanich (2006) Network



Link Importance Values and Rankings Under U-O and S-O Behavior



Relationship Between the Price of Anarchy and the Relative Total Cost Indices

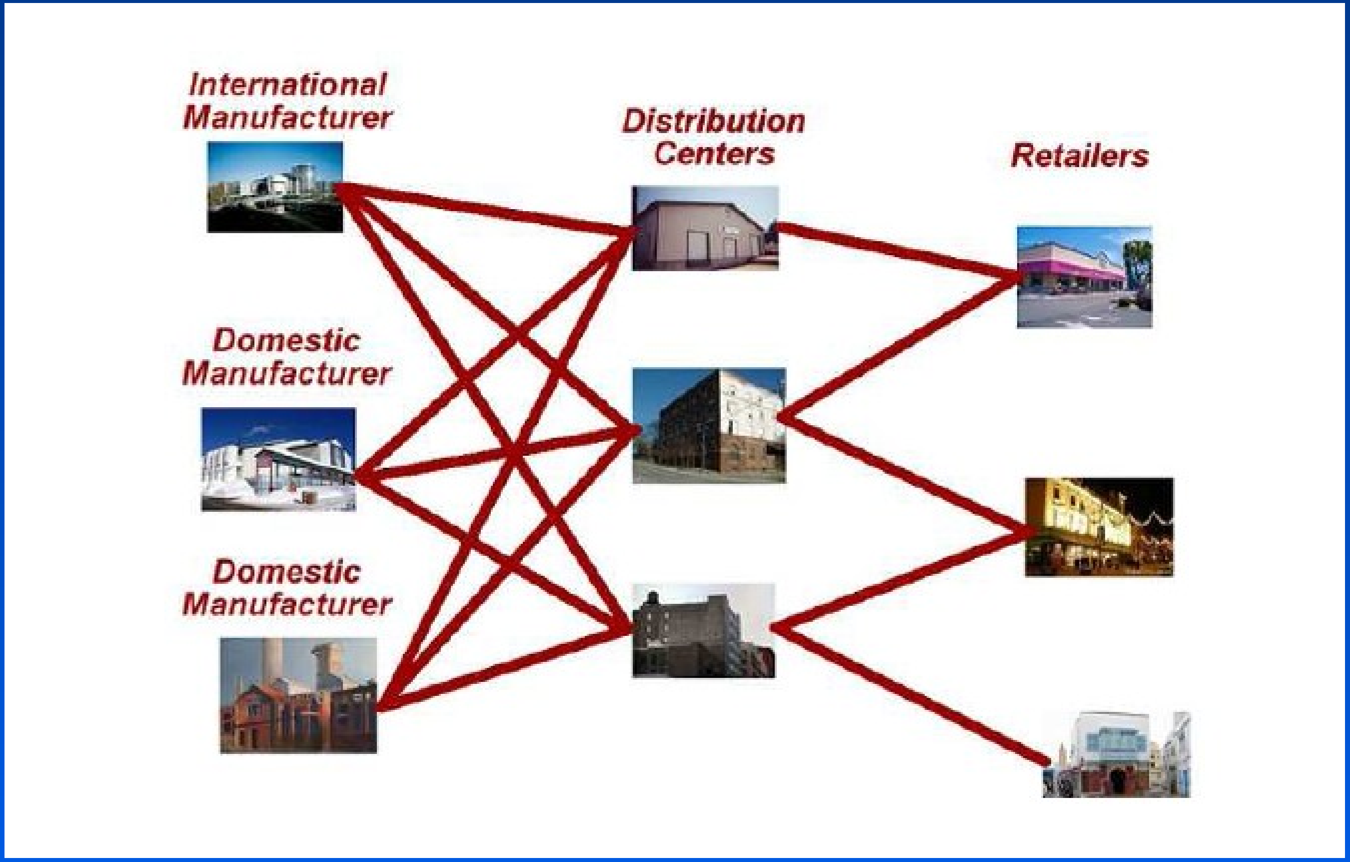
- ρ captures the relationship between total cost *across* distinct behavioral principles.
- The two relative total cost indices are focused on the degradation of network performance *within* U-O or S-O behavior.
- The relationship between the ratio of the two indices and the price of anarchy:

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

The result from the above ratio can be less than 1, greater than 1, or equal to 1, depending on the network and data.

Robustness in Supply Chains

Depiction of a Global Supply Chain



Supply Chain Disruptions

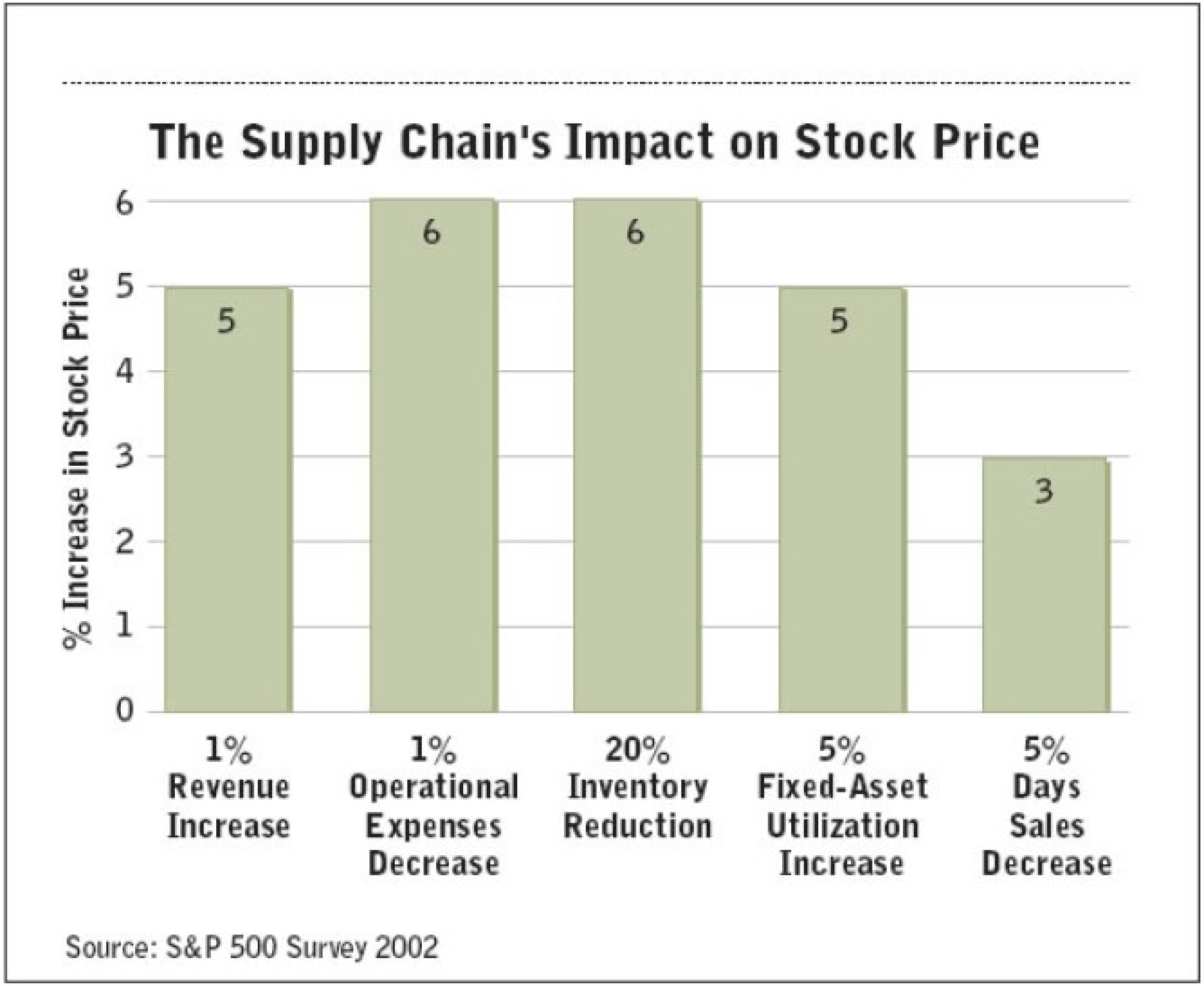
- In March 2000, a lightning bolt struck a Philips Semiconductor plant in Albuquerque, New Mexico, and created a 10-minute fire that resulted in the contamination of millions of computer chips and subsequent delaying of deliveries to its two largest customers: Finland's Nokia and Sweden's Ericsson.

- Ericsson used the Philips plant as its sole source and reported a $400 million loss because it did not receive the chip deliveries in a timely manner whereas Nokia moved quickly to tie up spare capacity at other Philips plants and refitted some of its phones so that it could use chips from other US suppliers and from Japanese suppliers.

- Nokia managed to arrange alternative supplies and, therefore, mitigated the impact of the disruption.

- Ericsson learned a painful lesson from this disaster.

The West Coast port lockout in 2002, which resulted in a 10 day shutdown of ports in early October, typically, the busiest month. 42% of the US trade products and 52% of the imported apparel go through these ports, including Los Angeles. Estimated losses were one billion dollars per day.

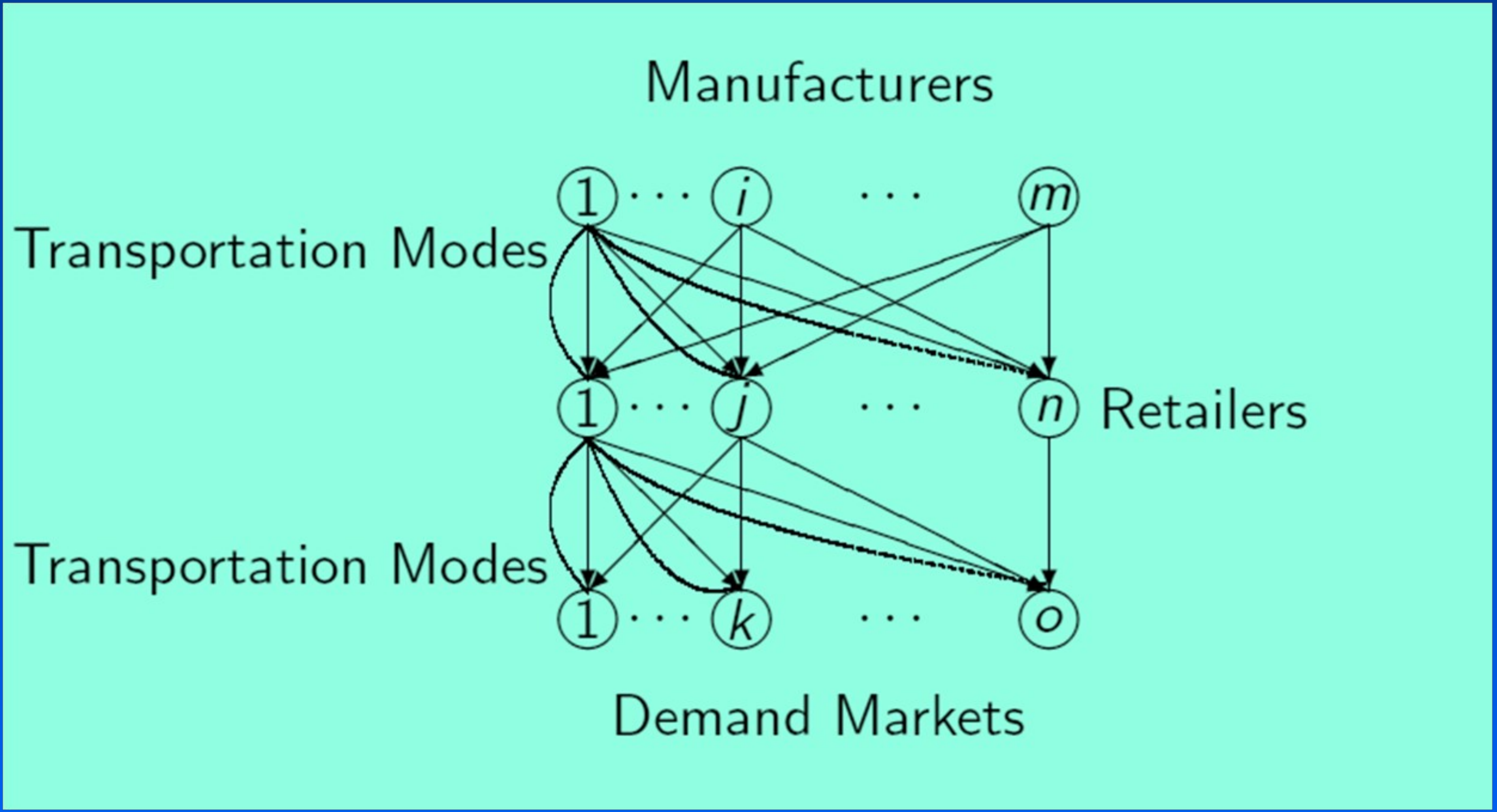


SUPPLY CHAIN MANAGEMENT REVIEW · MARCH 2005

As summarized by Sheffi (2005), one of the main characteristics of disruptions in supply networks is *the seemingly unrelated consequences and vulnerabilities stemming from global connectivity.*

Supply chain disruptions may have impacts that propagate not only locally but globally and, hence, a holistic, system-wide approach to supply chain network modeling and analysis is essential in order to be able to capture the complex interactions among decision-makers.

The Multitiered Network Structure of a Supply Chain



Assumptions

- Manufacturers and retailers are multicriteria decision-makers

- Manufacturers and retailers try to:

    - Maximize profit
    - Minimize risk
    - Individual weight is assigned to the risk level according to decision-maker’s attitude towards risk.

- Nash Equilibrium is the underlying behavioral principle.

A Supply Chain Network Performance Measure

The supply chain network performance measure, $\mathcal{E}^{SCN}$, for a given supply chain, and expected demands: $\hat{d}_k$; $k = 1, 2, \dots, o$, is defined as follows:

$$\mathcal{E}^{SCN} \equiv \frac{\sum_{k=1}^{o} \frac{\hat{d}_k}{\rho_{3k}}}{o},$$

where o is the number of demand markets in the supply chain network, and $\hat{d}_k$ and ρ_{3k} denote, respectively, the expected equilibrium demand and the equilibrium price at demand market k.

Supply Chain Robustness Measurement

Let $\mathcal{E}_w$ denote the supply chain performance measure with random parameters fixed at a certain level as described above. Then, the supply chain network robustness measure, $\mathcal{R}$, is given by the following:

$$\mathcal{R}^{SCN} = \mathcal{E}^0_{SCN} - \mathcal{E}_w,$$

where $\mathcal{E}^0_{SCN}$ gauges the supply chain performance based on the supply chain model, but with weights related to risks being zero.

Some of Our Relevant Papers for Module II

Environmental Impact Assessment of Transportation Networks with Degradable Links in an Era of Climate Change, Nagurney, Qiang, and Nagurney, *International Journal of Sustainable Transportation* 4: (2010), pp 154-171.

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