A Framework for Analyzing Efficiency-Robustness Trade-offs in the Design of Adaptable Complex Supply Networks

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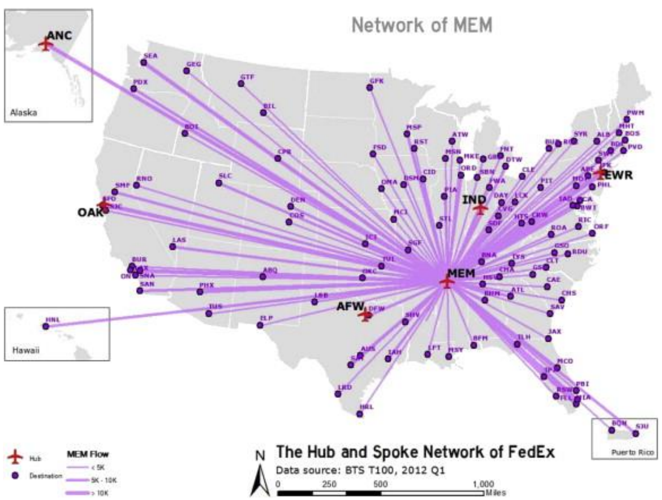
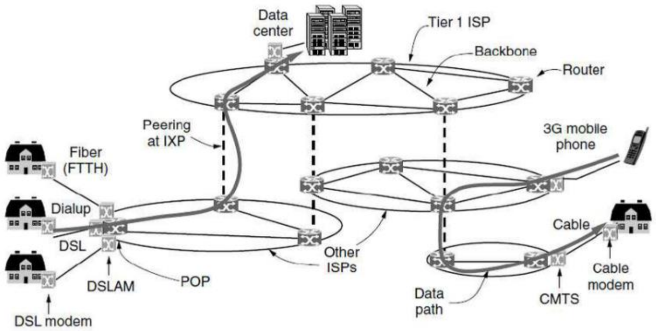
Complex Dynamical Networks

Process Industry Supply Chain

Western Electrical Power Grid



FedEx Transportation Network



Internet

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Source: Various CCL sources

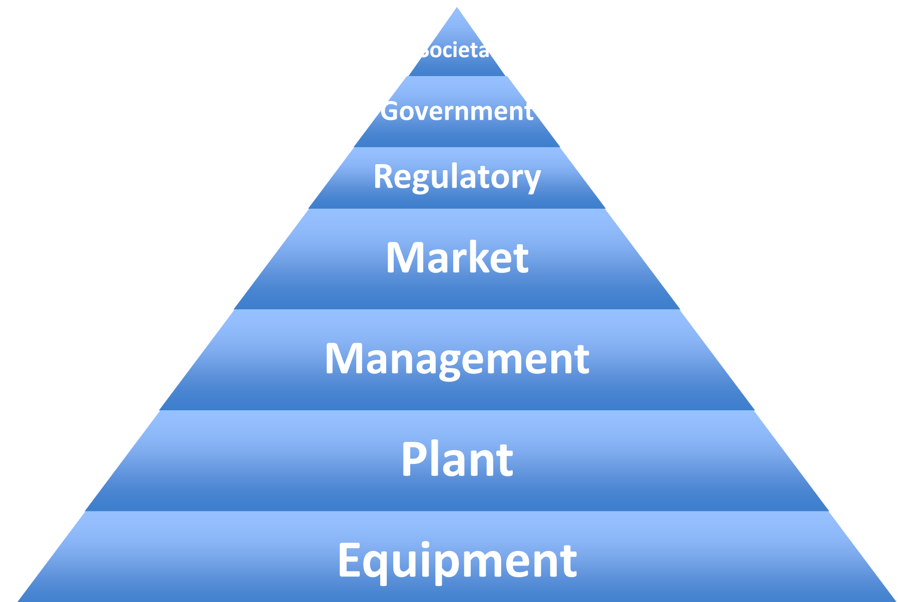
Pandemic-driven Supply Chain Failures

- **85%** of global supply chains have faced a reduction in operations due to the pandemic
- Operational performance reduced by
  - **57%** reported a drop of **25%**
  - **6%** reported complete shut down
  - Only **13%** reported normal operation
- Overconfidence was rife in the industry
  - **77%** anticipated to be at least "somewhat ready" for severe disruptions.
  - This number dropped to **39%** during the pandemic.

https://industryeurope.com/sectors/technology-innovation/study-85-of-supply-chains-hit-by-reductions-due-to-covid-19-pandemic/

Supply Chain as Socio-Technical Systems

- Supply chains are more than mere engineering systems
- Also involve humans making decisions
- Socio-technical system with self-interested agents
- Complex network of nonlinear interactions among equipment, processes, people, incentives, policies, and environment
- Modeling resilience requires a more comprehensive perspective



Seven-layer Hierarchical Model of Interactions

Picture credits:
https://www.google.com/search?q=workers+in+a+chemical+plant&biw=1280&bih=600&source=lnms&tbm=isch&sa=X&ved=0ahUKEwja74mm6bRAhWD7iYKHUZAAhEQ_AUIBigB#tbm=isch&q=operators+in+a+chemical+plant&imgrc=dRFrGrOp9_VbVM%3A
https://levelfiveexecutive.com/the-challenges-of-growth-when-running-a-board-of-directors/

What can we learn from Nature?

Natural systems are perhaps the most resilient

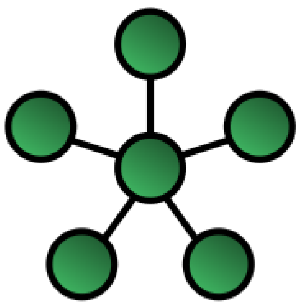
- Robustness to upsets: e.g. loss of species
- Distributed systems
- Decentralized control: e.g. ant foraging, swarms
- Evolutionary
- Adaptive
- Self-organized

Supply Chains Topology:
The Design Perspective

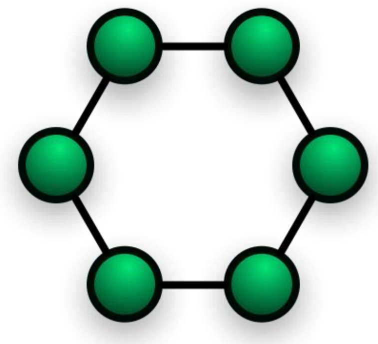
- Network Structure or Topology
  - What determines it?
  - How is it determined?
- Design Issues
  - Objective: Transport Material, Energy, Information
  - Metrics: Efficiency, Robustness/Resilience, and Cost
  - Environmental Constraints
- Central Design Question
  - How are the "local" properties of the network such as the vertex degree, which is a property at the individual node level, related to "global" or system-level properties such as network performance?
  - How do you go from Parts to Whole?

How Do We Design Resilient Topologies?

- Topology governs operational efficiency and resiliency



STAR Topology



RING Topology

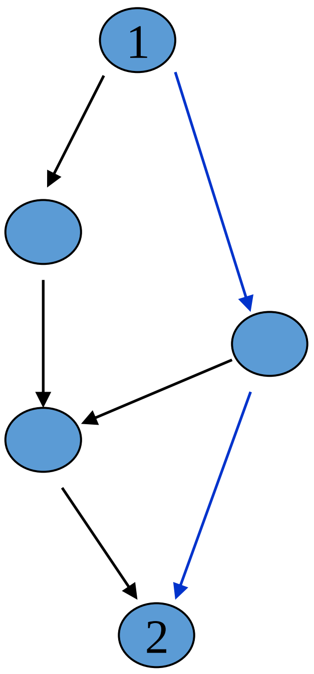
- How to optimize the topology in the event of threats and disruptions?

Efficiency

- Distance:

  d(i, j) = length of the *shortest* path between nodes i and j

- Average Path Length



$$\langle d \rangle = \text{Average APSP} = \frac{\sum_{i,j} d(i,j)}{\frac{n(n-1)}{2}}, \quad 1 \le i,j \le n$$

- Efficiency
  - Time, Energy, or Effort required for an exchange between agents i and j
  - Measured by Path Length
  - Smaller average path length, higher efficiency

$$Eff = \frac{1}{\langle d \rangle}$$

Robustness of Interaction

- Failure of one or more nodes or edges
  - ***Structural* robustness**:
    - Number of resulting component(s)
    - Resulting graph connected: perfectly robust
  - ***Functional* robustness**:
    - Efficiency of resulting component(s)
    - Average path length of resulting graph unchanged: perfectly robust
  - ***Worst-case* versus *average-case***

Overall Robustness: combination of above

Efficiency and Robustness

- They are often conflicting objectives
  - Increasing efficiency often implies reducing robustness for the same cost
  - And vice versa
- Efficiency : A measure of short-term performance or survival
- Robustness/Resilience: A measure of long-term performance or survival

Optimization Formalism

For a given environment α, design a network to maximize survival fitness G

$$\max\ G = \alpha\ \eta_E + (1-\alpha)\ \eta_R - c_1(\beta, k) - c_2(n)$$

η_E is the efficiency

η_R is the robustness

α is a constant, $0 \le \alpha \le 1$

c_1 is the cost function related to the addition of edges

c_2 is the cost function related to the addition of nodes

k is the vertex degree of the node to which a new edge is being added

β is the redundancy coefficient

n is the number of nodes

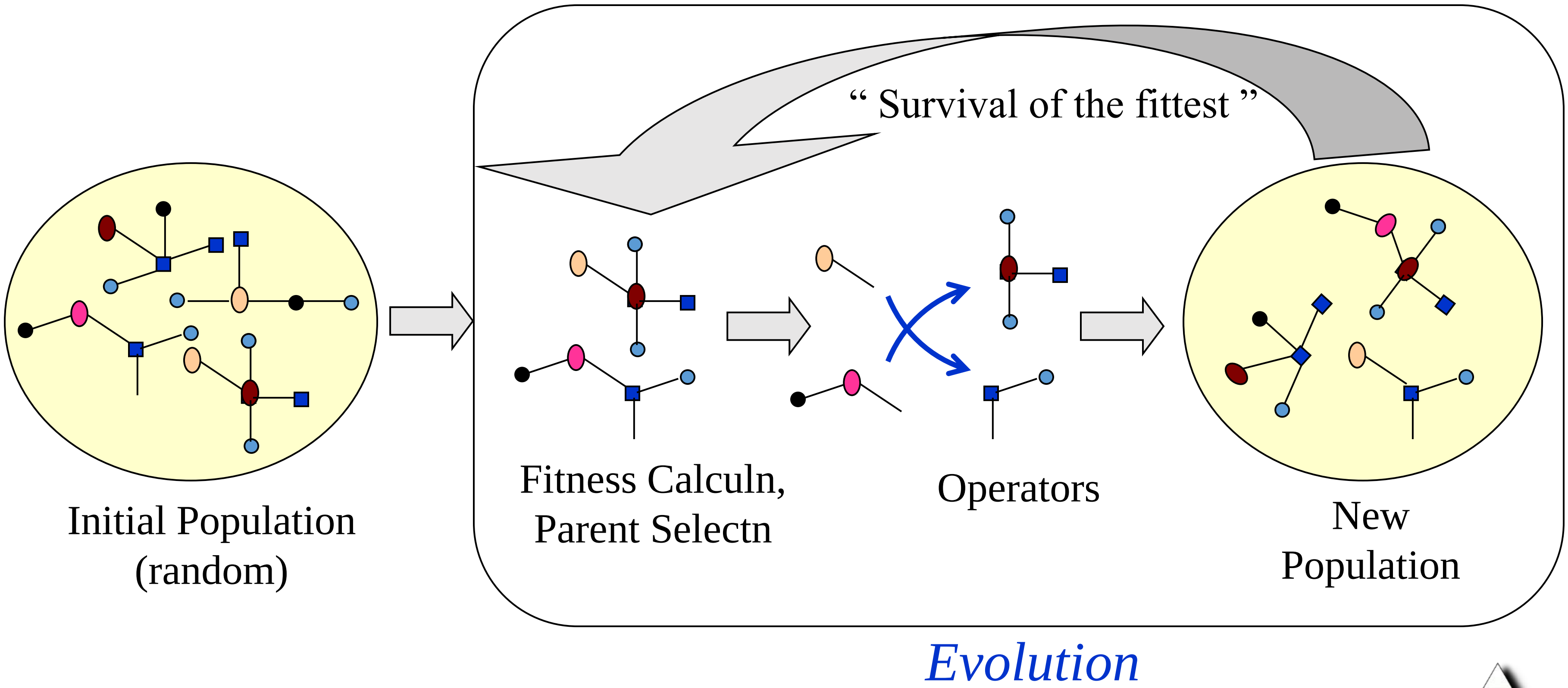
Venkatasubramanian, V., Katare, S., Patkar, P.R. and Mu, F.,
"Spontaneous emergence of complex optimal networks through evolutionary adaptation",
Computers and Chemical Engineering, 28(9), **2004.**

Different 'Survival' Environments α

- $\alpha = 0$
  - Only Robustness matters for survival
- $\alpha = 1$
  - Only Efficiency matters
- $\alpha = 0.5$
  - Both matter equally
- Other α values are possible

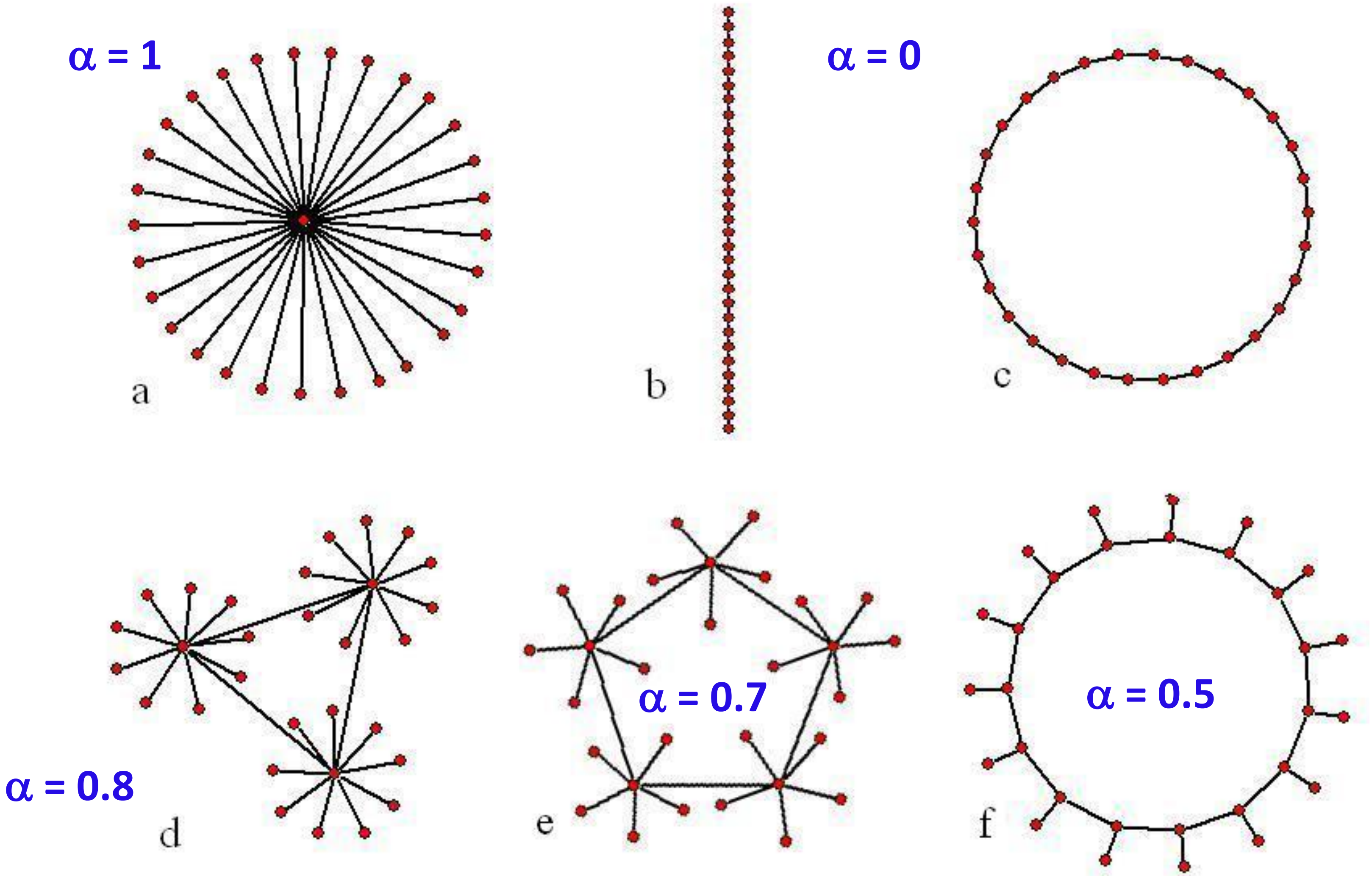
Adaptive Evolution of Topologies

- GAs – stochastic, evolutionary search based on the Darwinian model of natural selection



- Graphs represented as adjacency lists

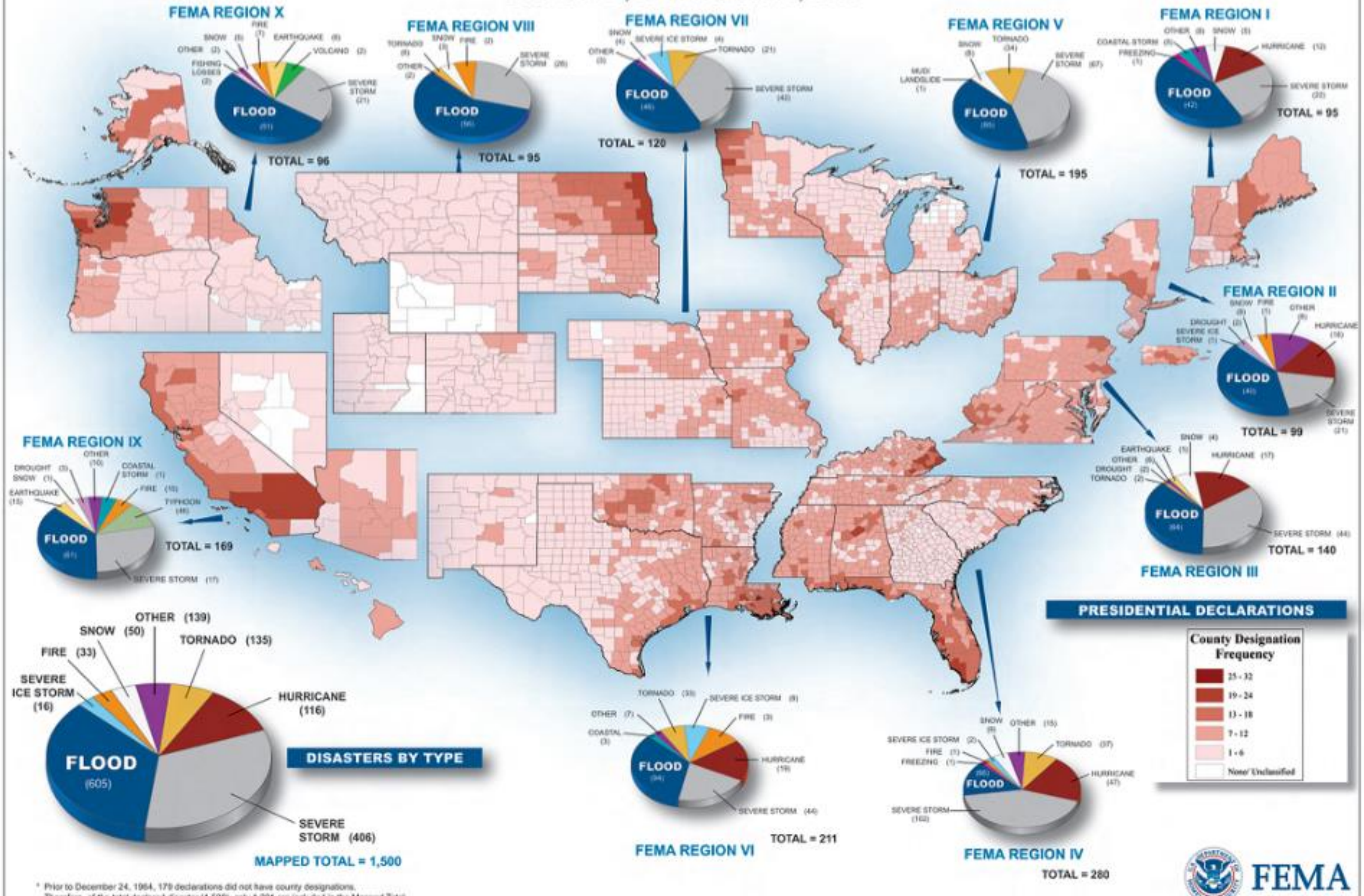
Optimal Network Topologies



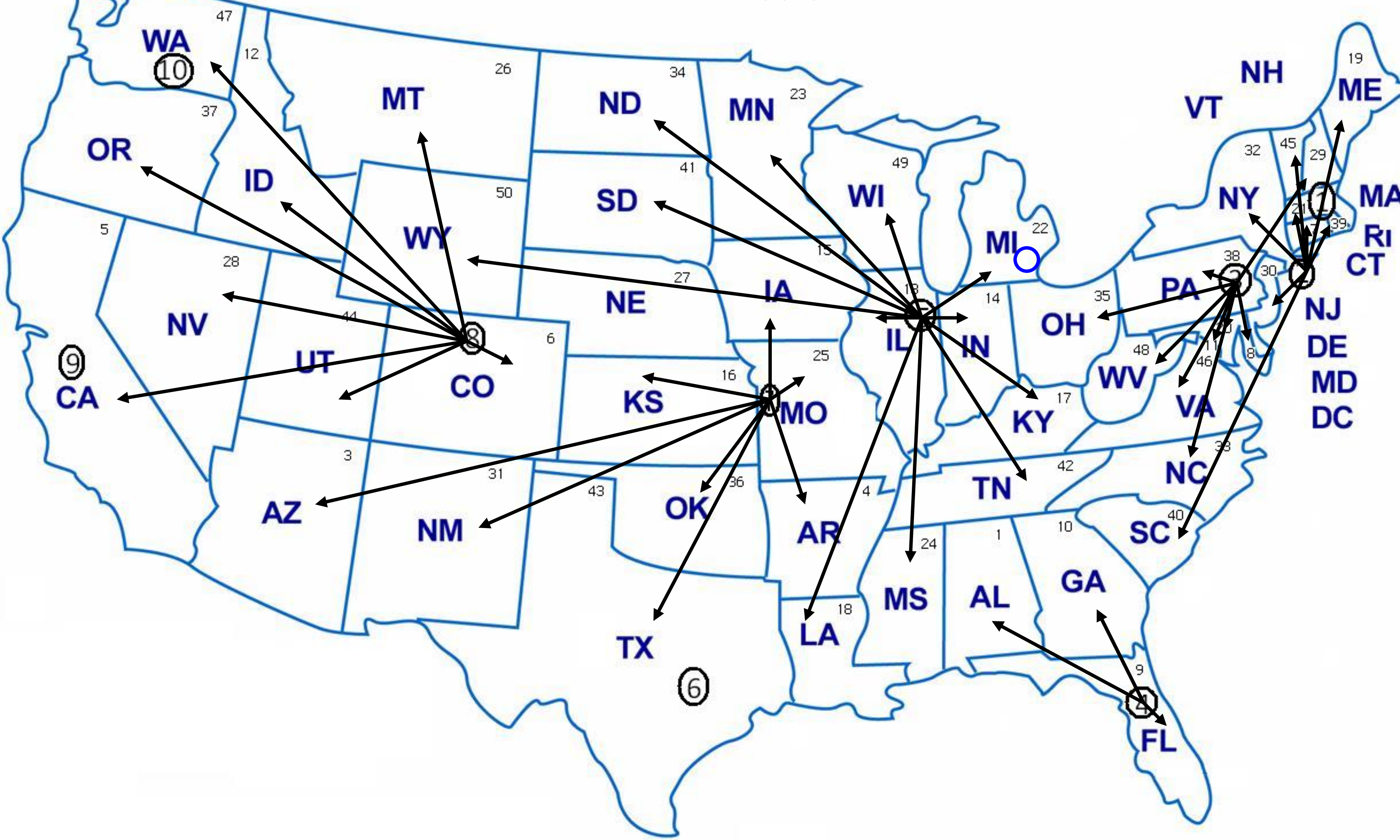
(a) Star (b) Line (c) Circle (d) Triangular Hub (e) Pentagonal Hub (f) Perfect Hub

PRESIDENTIAL DISASTER DECLARATIONS

December 24, 1964 to March 3, 2007

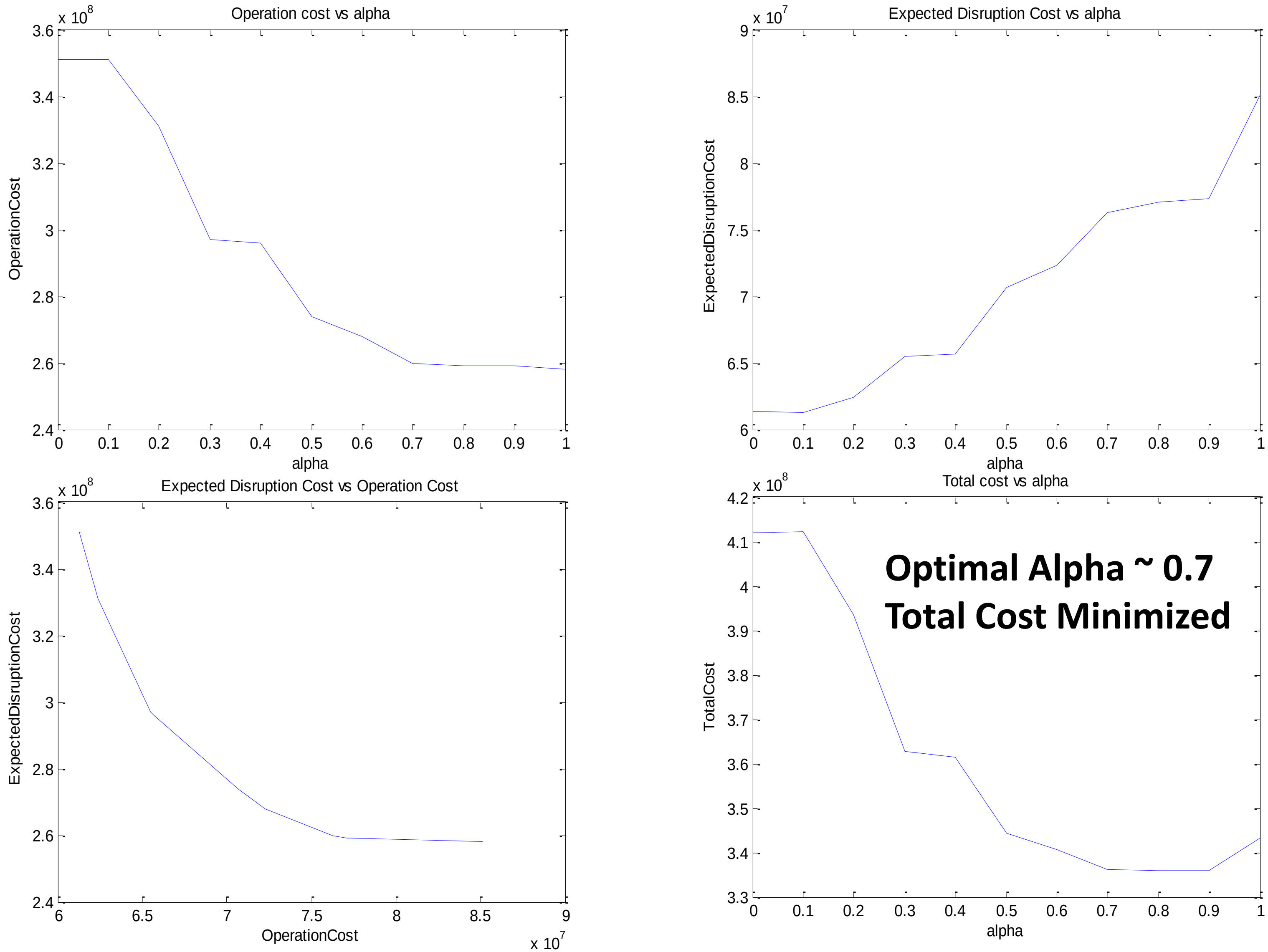


Automotive Supply Chain



<u>Jacksonville</u>	Houston	<u>Chicago</u>	Los Angeles	<u>Philadelphia</u>	<u>Kansas City</u>	<u>New York</u>	Seattle	Boston	<u>Denver</u>
<u>12.49%</u>	9.41%	<u>8.70%</u>	7.54%	<u>6.33%</u>	<u>5.35%</u>	<u>4.42%</u>	4.28%	4.24%	4.24%

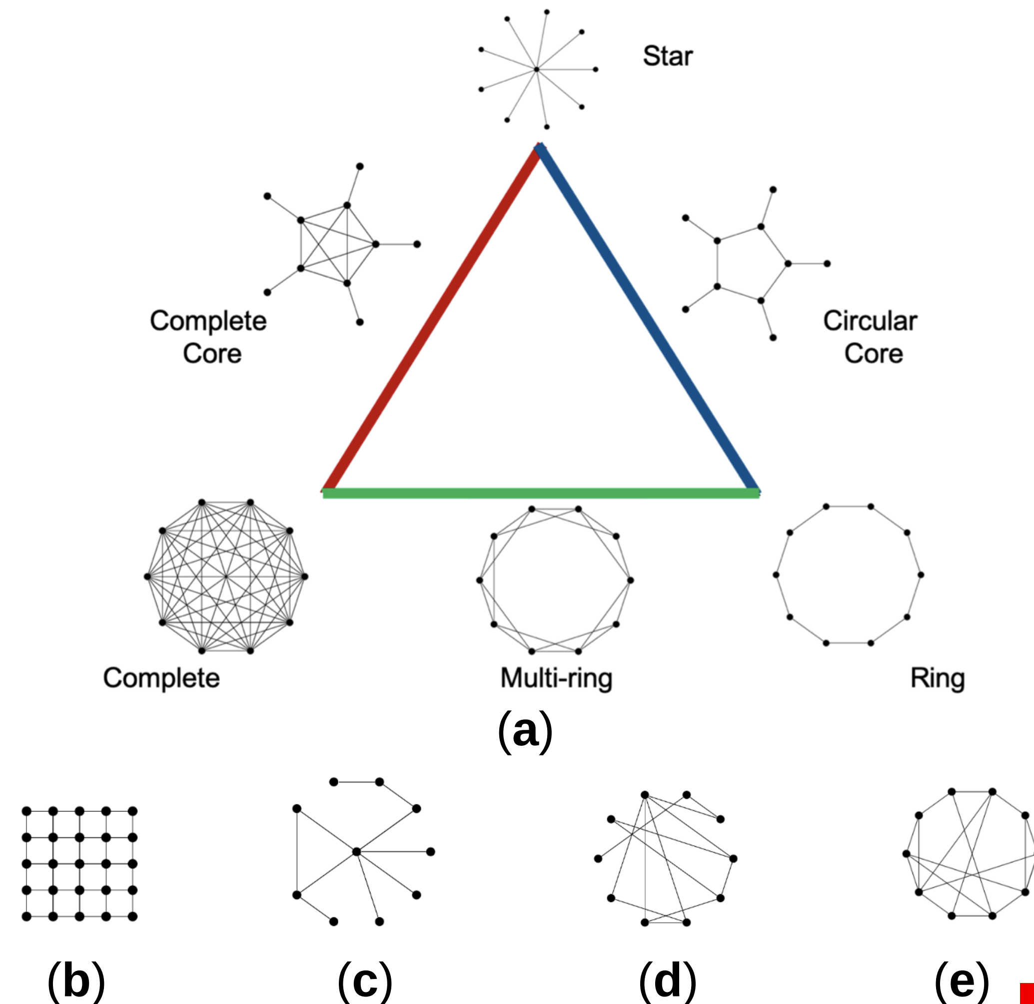
Disruption Cost vs Operating Cost Trade-off



Robust and Resilient Topologies in Hostile Environments

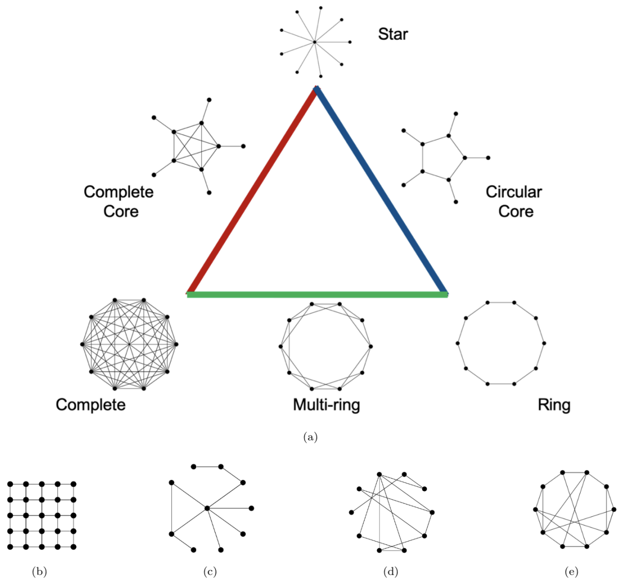
- Study the Efficiency-Robustness Tradeoffs
- Find the most efficient and robust/resilient topologies
- Perform well **consistently** under **hostile** conditions

(**a**) 240 network topologies
(**b**) von Neumann grid,
(**c**) Scale-free graph,
(**d**) Random graph
(**e**) Small-world graph

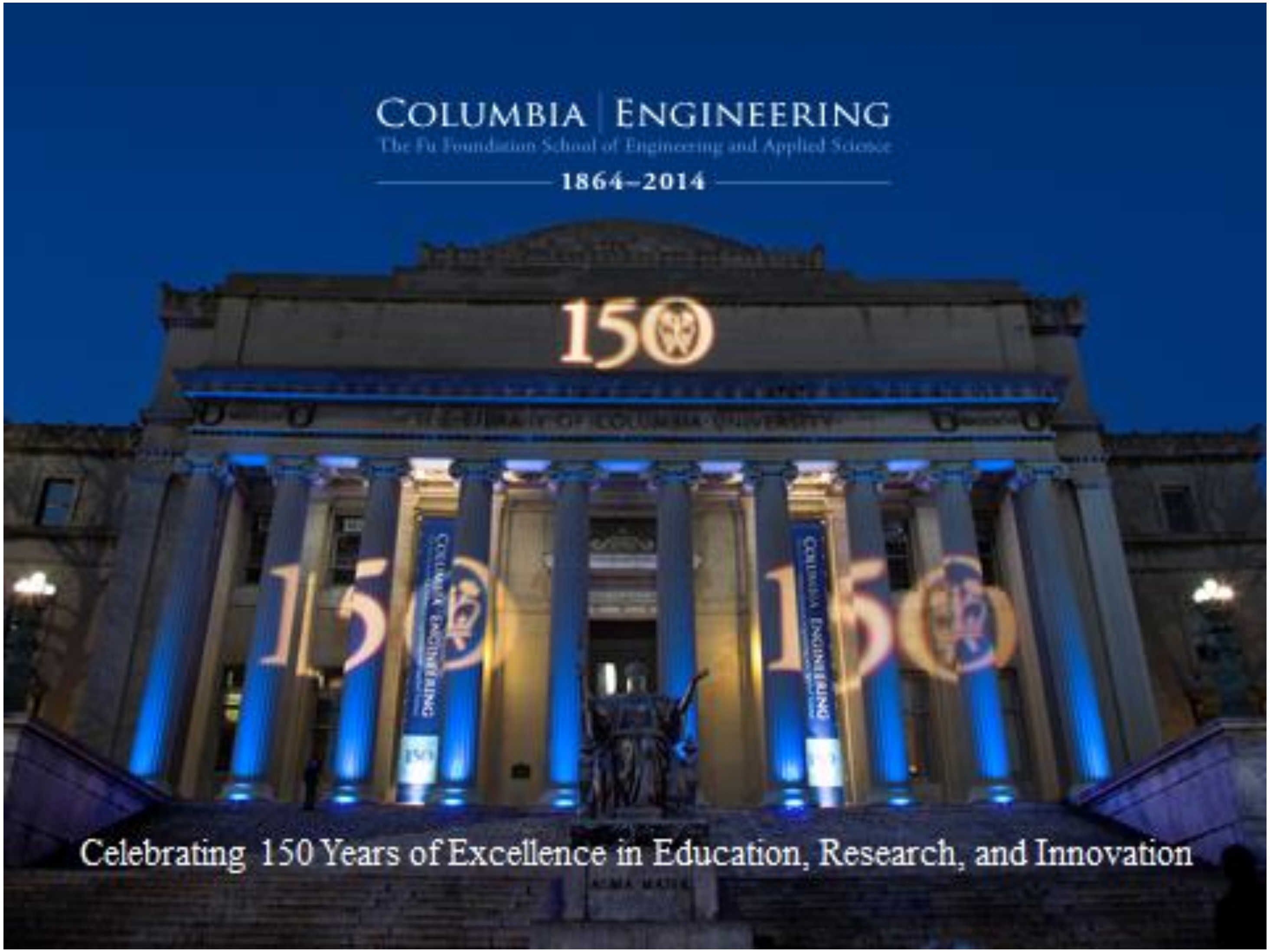


Summary

- Supply chains are complex dynamical networks
- Too much emphasis on efficiency while disregarding robustness and resilience issues
- Need to study optimal trade-offs between Efficiency and Robustness/Resilience
- Developed a formal analytical framework to study different topologies systematically



Thank You for Your Attention!



Questions?

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