Supply Chain Management under the Threat of Disruptions

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Outline

1. Motivation
2. State of the Art
3. Supply vs. Demand Uncertainty
4. Conclusions

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1. Motivation
   - Disruptions in Multi-Stage Systems
   - Modeling Supply Uncertainty
2. State of the Art
   - Inventory Models
   - Strategic Questions
   - Multi-Echelon Models
3. Supply vs. Demand Uncertainty
   - Introduction
   - Inventory Placement
   - Network Structure
   - The Cost of Reliability
4. Conclusions

Supply Chain Disruptions

- All supply chains are subject to disruptions
- Common sources
  - Natural disasters, weather
  - Strikes
  - Terrorism, war
  - Product defects
  - Equipment breakdowns
  - Transit/customs delays
  - Supplier bankruptcy
  - etc.
- Only recently have academics and practitioners studied supply disruptions in earnest

Why the Recent Interest in Disruptions?

- Supply chain disruptions are as old as supply chains:

East India Company

Wells Fargo

Why the Recent Interest? (cont'd)

1. Recent high-profile disruptions
   - September 11 (2001)
   - West-coast port lockout (2002)
   - Flu vaccine shortage (2004)
   - Hurricanes Katrina and Rita (2005)
   - Bird-flu pandemic (???)

Why the Recent Interest? (cont'd)

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   - Flu vaccine shortage (2004)
   - Hurricanes Katrina and Rita (2005)
   - Bird-flu pandemic (???)
2. Focus on lean supply chain management
   - aka just-in-time (JIT), etc.
   - Systems contain very little slack
   - Very efficient—as long as there is little uncertainty
   - Very fragile—easily disrupted
   - **There is value to having slack in a system.**

Why the Recent Interest? (cont'd)

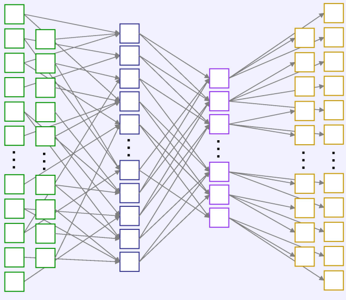
3. Increasingly global supply chains
    - A single supply chain may span the globe
    - Firms are less vertically integrated
        - "Manufacturing" firms may actually manufacture very little
        - Instead, they assemble components that are made by suppliers
        - Thomas Friedman, *The World is Flat*
    - Firms depend critically on parts from unstable regions
        - Unstable politically, economically, militarily, climatologically, seismically, ...
        - Barry Lynn, *End of the Line*

Cascading Disruptions

- Supply chains consist of many locations ("stages")
- Stages are grouped into tiers ("echelons")
- Disruptions are never purely local
- They cascade through the system
- Upstream disruptions cause downstream stockouts

Cascading Disruptions: GM Example

- In 1998, strikes at two General Motors parts plants



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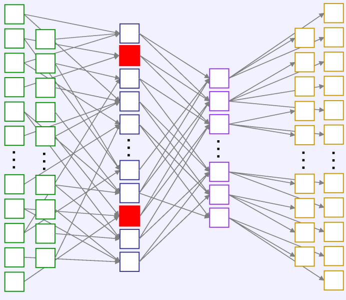

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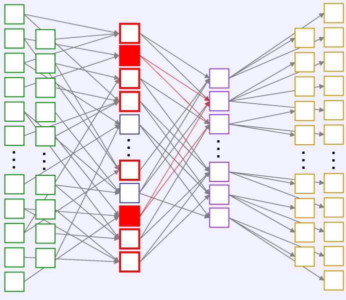

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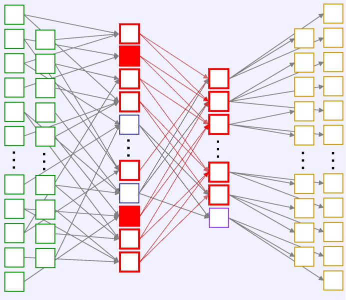

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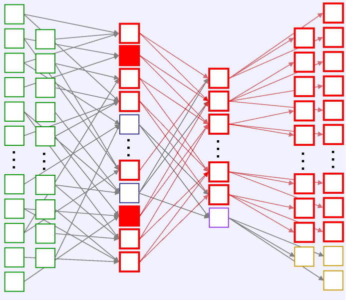

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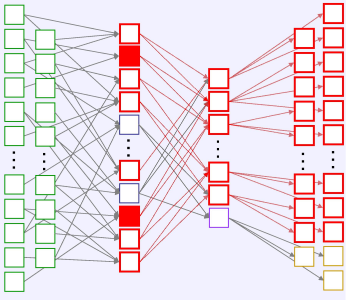
- 500K cars, 37% ↓ sales, 33% ↓ market share, $809M qrtly loss



A Scarier Example

- A terrorist attack on New York Harbor in winter would halt shipments of heating fuel
- New England and upstate New York would run out of heating fuel within 10 days
  - (according to national security analysis)
- Even a temporary halt would have significant cascading effects

Source: Finnegan (2006)

Most Research is on Single-Stage Systems

- Despite the importance of studying disruptions in a multi-stage context, most research focuses on a single stage
  - e.g., how should a firm plan for disruptions to its suppliers or itself?
  - Examines purely local effects
- (There are a few exceptions)
- I will discuss some insights about disruptions in multi-stage systems

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    5. Pop-Tarts

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- Demand management
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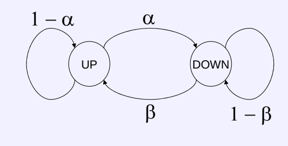
  - Airlines?
- Demand management
  - After 1999 Taiwan earthquake, Dell shifted demand to lower-memory PCs
- Acceptance

Except the last two, these are all **proactive** strategies.

Modeling Disruptions

- Typically, disruptions modeled as a **Markov process**
- In each period, a given stage is either UP or DOWN
- α = failure prob. = P(DOWN next period|UP this period)
- β = recovery prob. = P(UP next period|DOWN this period)
- Length of time stage is UP is geometrically distributed
  - Same for DOWN
- Can make it more general
- Parameter estimation can be a big problem



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A **Brief** Overview of Inventory Theory

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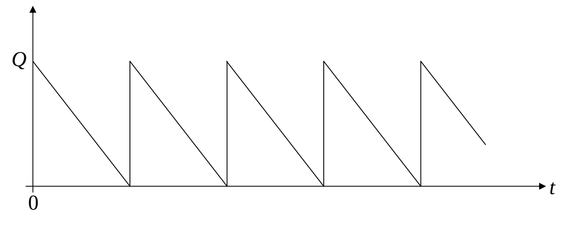
- Deterministic models
  - Key tradeoff: Fixed vs. holding cost
  - i.e., place large orders or small?
- Stochastic models
  - Usually stochastic demand
    - Usually normally distributed or similar
  - Key tradeoff: Holding vs. stockout cost
  - Some models also include fixed cost

The Economic Order Quantity (EOQ) Model

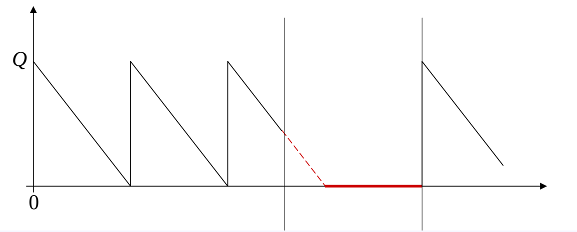
- Demand is deterministic, constant
- Fixed cost to order, holding cost to store inventory
- Inventory curve:



- Objective: Find optimal Q to minimize average cost per year
- Harris (1913)

EOQ with Disruptions

- Now suppose supplier may be “down” when firm places order



- Harder to find optimal Q
- Parlar and Berkin (1991), Berk and Arreola-Risa (1994)
- Order before inventory hits 0: Parlar and Perry (1995, 1996)
- Stochastic demand: Gupta (1996), Parlar (1997), Mohebbi (2003, 2004)

The Newsboy Problem

- Or my version: The Hot Dog Stand Problem

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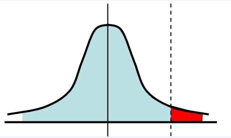
- Each morning, hot dog vendor goes to supplier to buy hot dogs
- Daily demand is random
- No opportunity to buy more if he runs out
- Leftover hot dogs can be kept until tomorrow, at a cost
- How many hot dogs should he buy?

The Newsboy Problem (cont'd)

- Optimal # to buy = mean + some number of SD's
- Optimal # of SD's depends on holding and stockout cost



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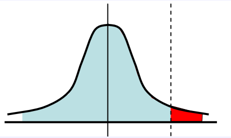


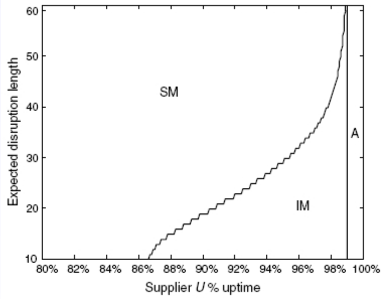
- Optimal # to buy = mean + some number of SD's
- Optimal # of SD's depends on holding and stockout cost
- Now suppose supplier may experience disruptions
  - But demand is deterministic
- Maybe buy extra hot dogs today in case supplier is down tomorrow
- Optimal order quantity has same form
  - But distribution refers to supply, rather than demand
  - Tomlin (2006)

Disruptions in Inventory Models

- Starting in the early 1990s, disruptions embedded into classical inventory models
- All are single-stage models
- Most must be solved numerically
  - Even if non-disruption models can be solved analytically
- General insight:
  - Hold more inventory

Strategic Questions

- More recently, papers addressing strategic questions
- What strategy is optimal?
- How does this change as disruption characteristics change?
- Tomlin (2006)

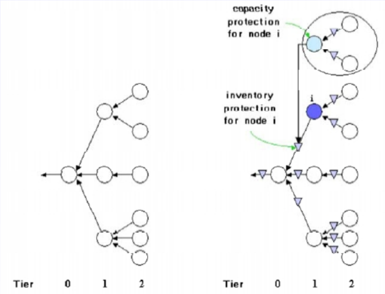


Strategic Questions, (cont'd)

- Extensions:
  - Supplier flexibility: Tomlin and Wang (2004)
  - Advanced warning: Tomlin and Snyder (2006)
- Effect of border closures: Lewis, Erera, and White (2005)
- Error from "bundling" disruptions and yield uncertainty: Chopra et al. (2005), Schmitt and Snyder (2006)

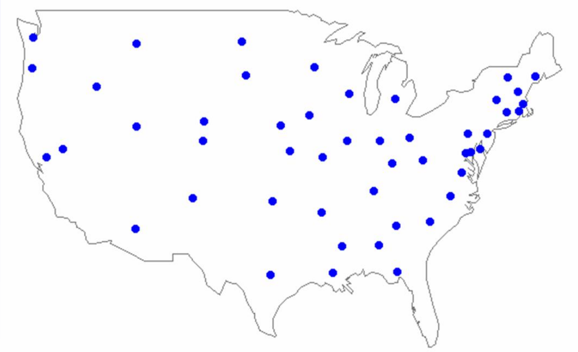
Multi-Echelon Models

- Kim et al. (2005)
  - Yield uncertainty in 3-echelon SC, risk-averse objective
- Hopp and Yin (2006)
  - Optimal placement and size of inventory and capacity buffers in assembly network
  - More severe upstream disruptions $\Longrightarrow$ buffers further upstream



Facility Location Problems

- Nodes represent demand locations
- Where to open facilities? (plants, warehouses, distribution centers, etc.)



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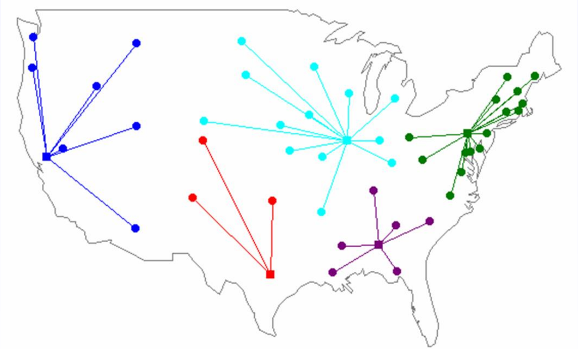
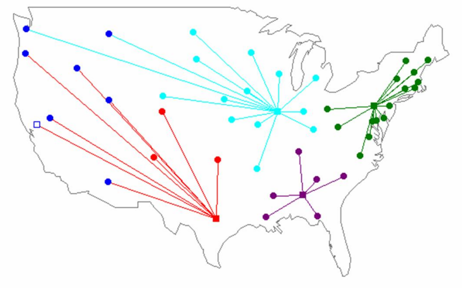


Facility Location with Disruptions

- How to choose facility locations so that the supply chain network is resilient to facility disruptions?



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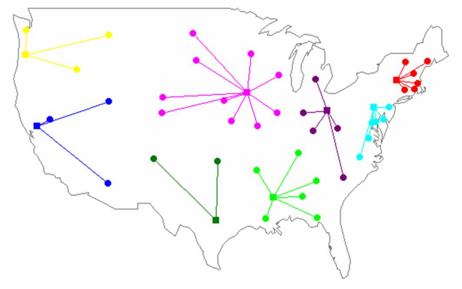

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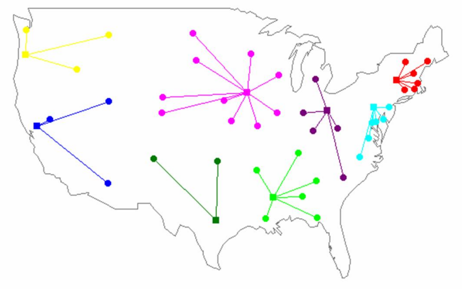

- Snyder and Daskin (2005), Berman et al. (2004), Church and Scaparra (2005), Qi et al. (2006)
- Tendency toward diversification: More facilities open than in classical models

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Supply vs. Demand Uncertainty

- Demand uncertainty (DU):
  - Randomness in demand quantity, timing, product mix, etc.
- Supply uncertainty (SU):
  - Disruptions
  - Yield uncertainty
  - Lead-time uncertainty
  - etc.

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- Demand uncertainty (DU):
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- Supply uncertainty (SU):
  - Disruptions
  - Yield uncertainty
  - Lead-time uncertainty
  - etc.
- Under both DU and SU, the main issue is the same:
  - Not enough supply to meet demand
  - May be irrelevant whether the mismatch came from DU or SU

Are DU and SU The Same?

1. The mitigation strategies described a few minutes ago can be used for DU, too
   - Additional inventory, multiple suppliers, etc.
2. Newsboy model under SU is "mirror image" of that under DU

- Clearly there is some relationship between them.

Good News and Bad News

- The good news:
  - We have been studying supply chains under DU for decades
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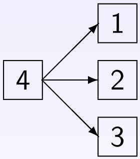
- The good news:
  - We have been studying supply chains under DU for decades
  - We know a lot about them
- The bad news:
  - The "conventional wisdom" from DU is often **wrong** under SU
- We need to study supply chains under SU

Supply vs. Demand Uncertainty

- The optimal strategy under SU may be exactly opposite from that under DU
- Next up: A series of studies demonstrating this
- All consider multi-echelon supply chains
- Some results can be proven theoretically, others are demonstrated using simulation
- I will use terms like "firms" and "retailers"
  - But results are equally applicable to military, health care, humanitarian, and other non-commercial supply chains
- See Snyder and Shen (2006) for more details

Centralization vs. Decentralization

- Consider a system with one warehouse and N retailers
- Let's assume:
  - Cost of holding inventory is equal at the two echelons
  - Lead times are negligible



Key Question

Should we hold inventory at the warehouse or at the retailers?

Answer under DU

- Suppose each retailer has mean demand μ and SD σ
- Can show total cost is proportional to σ
- In decentralized system (hold inventory at retailers):
  - Total cost at one stage is proportional to σN
- In centralized system (hold inventory at warehouse):
  - Demand seen by warehouse has SD $\sigma\sqrt{N}$
  - Therefore total cost is proportional to $\sigma\sqrt{N}$
- Centralization is optimal
- This is the famous **risk-pooling effect** (Eppen 1979)

Answer under SU

- Suppose inventory sites are subject to disruptions
- Deterministic demand, $= \mu$ at each retailer
- In the decentralized system, a disruption affects only one retailer
- In the centralized system, a disruption affects the whole supply chain

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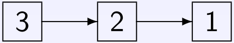
  - A given retailer is disrupted the same % of time in either
- Variance of cost:
  - The **variance of cost** is smaller in the decentralized system
  - Proportional to N^2d^2 in centralized system
  - Proportional to Nd^2 in decentralized system

The Risk-Diversification Effect

- Therefore, under SU, decentralization is “optimal”
- Disruptions are equally frequent in either system but less severe in the decentralized one
- We call this the **risk-diversification effect**

Upstream vs. Downstream

- Consider a “serial” supply chain
- Cost of holding inventory is non-increasing as we move downstream
- Lead times are negligible



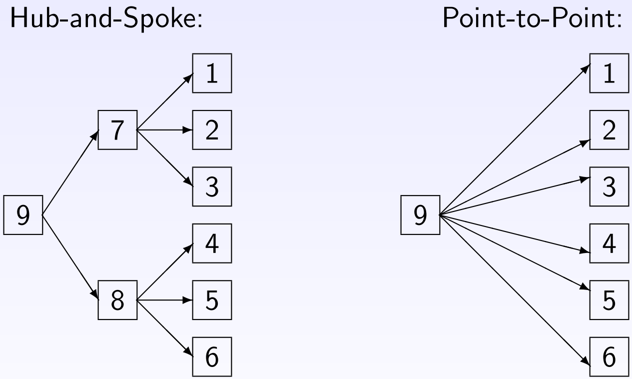
Key Question

Should we hold inventory upstream or downstream?

Inventory Placement, cont'd

- Under DU, conventional wisdom says hold inventory upstream
  - Holding costs increase as we move downstream
- But under SU, downstream inventory may be preferable
  - Protects against stockouts anywhere in the system
  - Depends on relative holding costs

Hub-and-Spoke vs. Point-to-Point Systems



Key Question

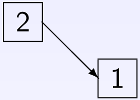
Which type of network is preferred?

Hub-and-Spoke vs. Point-to-Point Systems, cont'd

- Under DU, hub-and-spoke systems are optimal
  - Due to **risk-pooling effect**: fewer stocking locations $\Longrightarrow$ smaller inventory requirement
- Under SU, point-to-point systems are optimal
  - Due to **risk-diversification effect**: more stocking locations $\Longrightarrow$ reduced severity of disruptions

Supplier Redundancy

- Consider a single retailer with one or more suppliers
- Suppliers are identical in terms of cost, capacity, reliability



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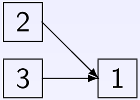

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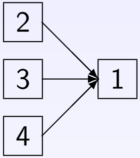

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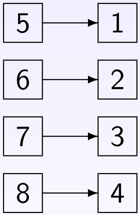
Supplier Redundancy, cont'd

- Under DU, second supplier provides value if capacities are tight
  - e.g., if capacity $= \mu + \sigma$
  - But value decreases quickly as capacity increases
  - Third, etc. suppliers provide little value
- Under SU, second supplier provides great benefit
  - Fills in when primary supplier is disrupted
  - Also helps ramp back up after disruption
  - Even third+ supplier provides some benefit

Supplier Flexibility

- Related concept: **supplier flexibility**
- Multiple suppliers, multiple retailers
- Results are similar
- Closely related to **process flexibility** (Jordan and Graves 1995)
  - Bipartite network of jobs and workers
  - How much cross-training is required?
  - i.e., how dense should network be?



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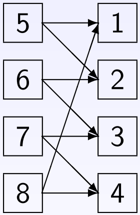

Supplier Flexibility

- Related concept: **supplier flexibility**
- Multiple suppliers, multiple retailers
- Results are similar
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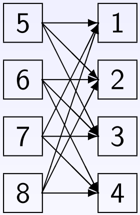

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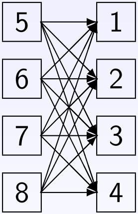
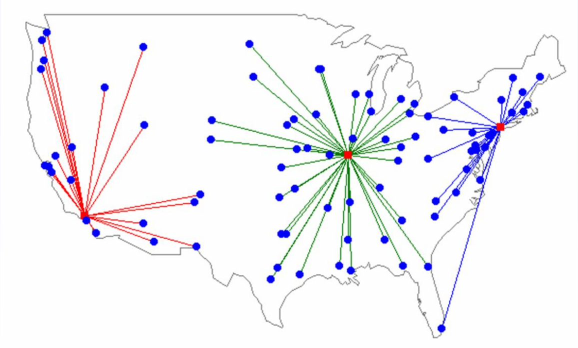


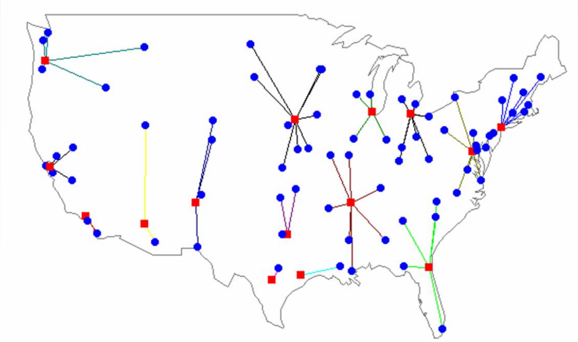
Facility Location under DU

- Tendency toward **consolidation**
- Open fewer facilities due to risk-pooling effect and economies of scale (Daskin, Coullard, and Shen 2002)



Facility Location under SU

- Tendency toward **diversification**
- Open more facilities due to risk-diversification effect (Snyder and Daskin 2005)
- More recent model finds balance between the two under both DU and SU (Jeon and Snyder 2006)



The Cost of Reliability

- Firms are used to planning for DU
- Often reluctant to plan for SU if it requires large investment in inventory or infrastructure

Key Question

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The Cost of Reliability

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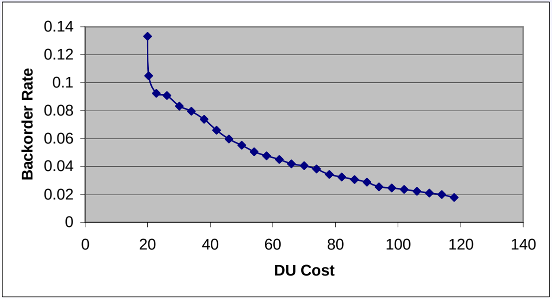
Key Question

How much DU cost must be sacrificed to achieve a given level of reliability?

- The short answer: Not much

Tradeoff Curve

- Each point represents a solution
  - Left-most point is "optimal" solution considering DU only
  - Second point: 21% fewer stockouts, 2% more expensive
- "Steep" left-hand side of tradeoff curve is fairly typical
  - Especially for combinatorial problems



Outline

1. Motivation
   - Disruptions in Multi-Stage Systems
   - Modeling Supply Uncertainty
2. State of the Art
   - Inventory Models
   - Strategic Questions
   - Multi-Echelon Models
3. Supply vs. Demand Uncertainty
   - Introduction
   - Inventory Placement
   - Network Structure
   - The Cost of Reliability
4. Conclusions

Conclusions

- Optimal strategy under SU is often exact opposite from that under DU
  - That's not to say firms are doing everything wrong
  - But SU should be accounted for more than it is
  - Strategy chosen should account for both
- Many of these results boil down to **risk-diversification effect**
  - Disruptions are less severe when eggs aren't all in one basket
- Tradeoff between cost and reliability is often steep
  - Large improvements in reliability with small increases in cost

My Research Wish List

- Strategies for modeling and mitigating cascading of disruptions
- Methods for identify bottlenecks/vulnerability points
- Methods for identifying buffer points
- Good models (or approximations) that include both DU and SU
- Formal relationship between DU and SU
- Robust models: Insensitive to errors in disruption parameters

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Questions?

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