Managing Supply Chain Risks

Flexibility – From Practice to Theory

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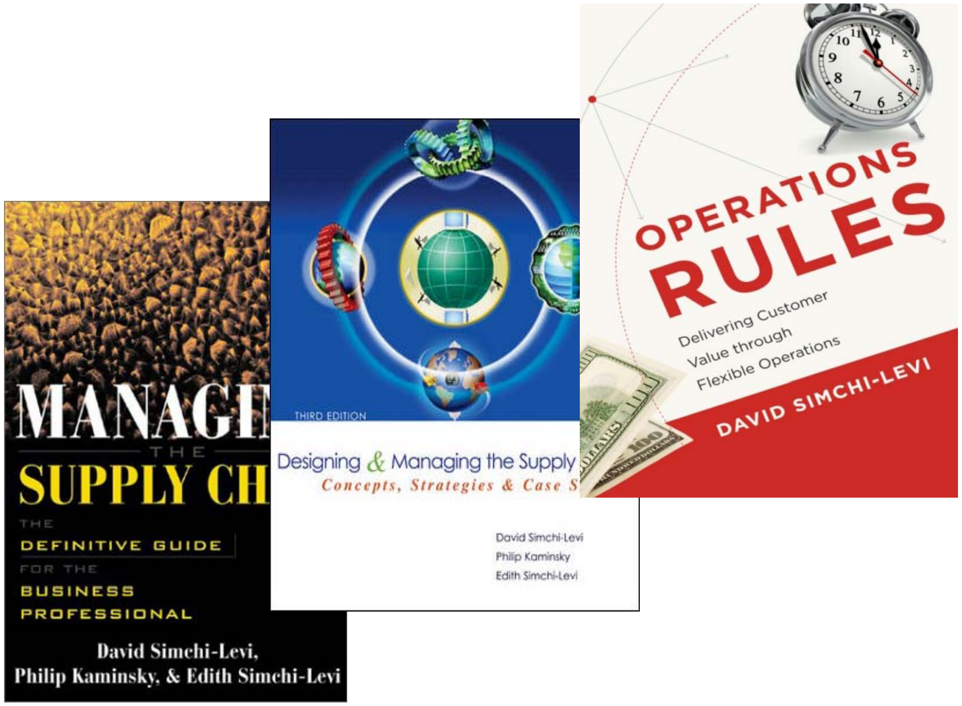
Joint work with Yehua Wei

OPERATIONS RESEARCH CENTER

What We'll Cover …

- **Introduction to Flexibility**
- **Model and Motivating Examples**
- **Supermodularity in Long Chains**
- **Additivity in Long Chains**
- **Summary**



Supply Chain Flexibility: Introduction

- The ability to respond, or to react, to change:
  - Demand volume and mix
  - Commodity prices
  - Labor costs
  - Exchange rates
  - Regulations and trade policies
  - Supply chain disruption
  - ……
- The objective is to
  - Reduce cost
  - Maintain business cash flow
  - Reduce the amount of unsatisfied demand
  - Improve capacity utilization
- With no, or little, penalty on response time

Achieving Flexibility through….

- Product design
  - Modular product architecture, Standardization, Postponement, Substitution
- Process design
  - Lean Strategies: Flexible work force, Cross-Training, Visibility & Speed, Collaboration, Organization & Management structure
  - Procurement Flexibility: Flexible contracts, Dual sourcing, Outsourcing, Expediting
- System design
  - Capacity flexibility, Manufacturing flexibility, Distribution flexibility

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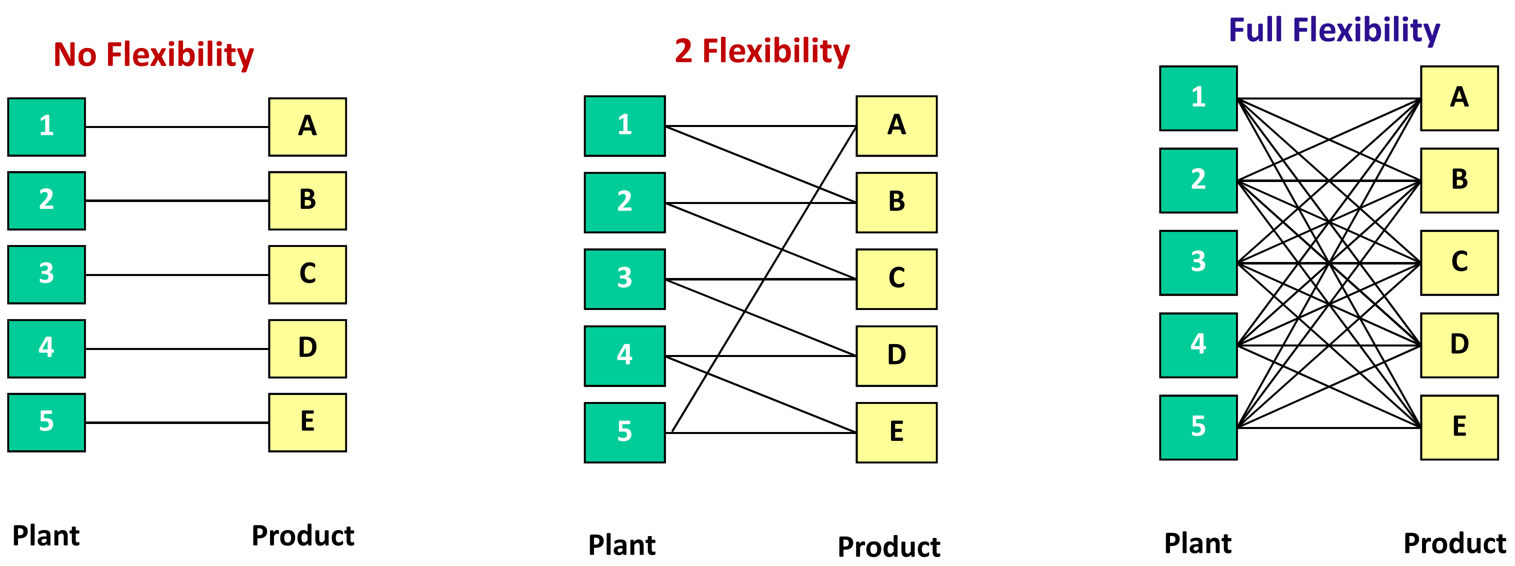
Flexibility through System Design

- **Balance transportation and manufacturing costs**
- **Cope with high forecast error**
- **Better utilize resources**



Case Study: Flexibility and the Manufacturing Network

- Manufacturer in the Food & Beverage industry.
- Currently each product family is manufactured in one of five domestic plants.
- Manufacturing capacity is in place to target 90% line efficiency for projected demand.
- Objectives:
  - Determine the cost benefits of manufacturing flexibility to the network.
  - Determine the benefit that flexibility provides if demand differs from forecast;
  - Determine the appropriate level of flexibility

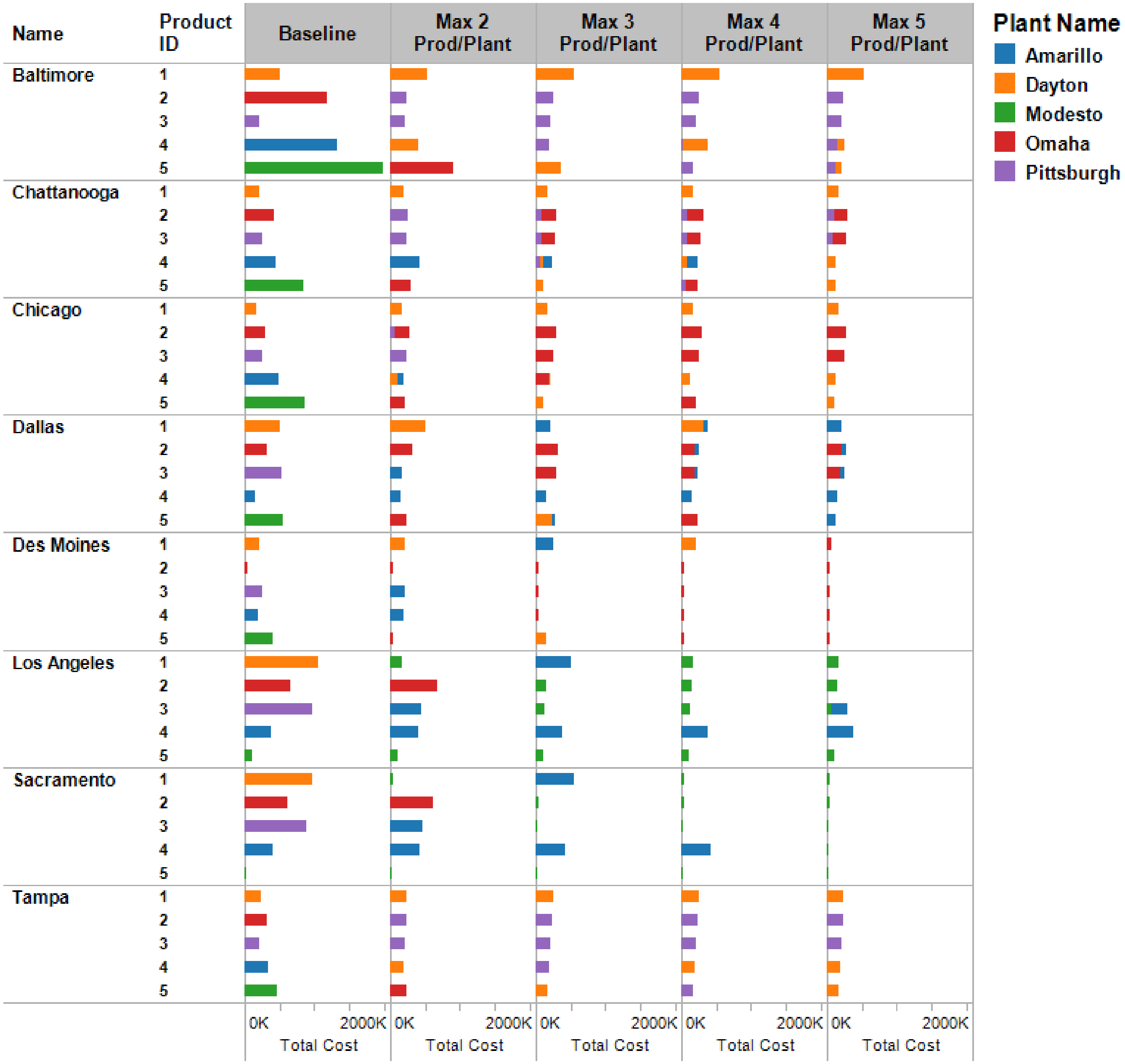
Summary of Network

- **Manufacturing is possible in five locations with the following average labor cost:**
  - Pittsburgh, PA $12.33/hr
  - Dayton, OH $10.64/hr
  - Amarillo, TX $10.80/hr
  - Omaha, NE $12.41/hr
  - Modesto, CA $16.27/hr
- **8 DC locations: Baltimore, Chattanooga, Chicago, Dallas, Des Moines, Los Angeles, Sacramento, Tampa**
- **Customers aggregated to 363 Metropolitan Statistical Areas & 576 Micropolitan Statistical Areas**
  - Consumer product- Demand is very closely proportional to population
- **Transportation**
  - Inbound transportation Full TL
  - Outbound transportation LTL and Private Fleet

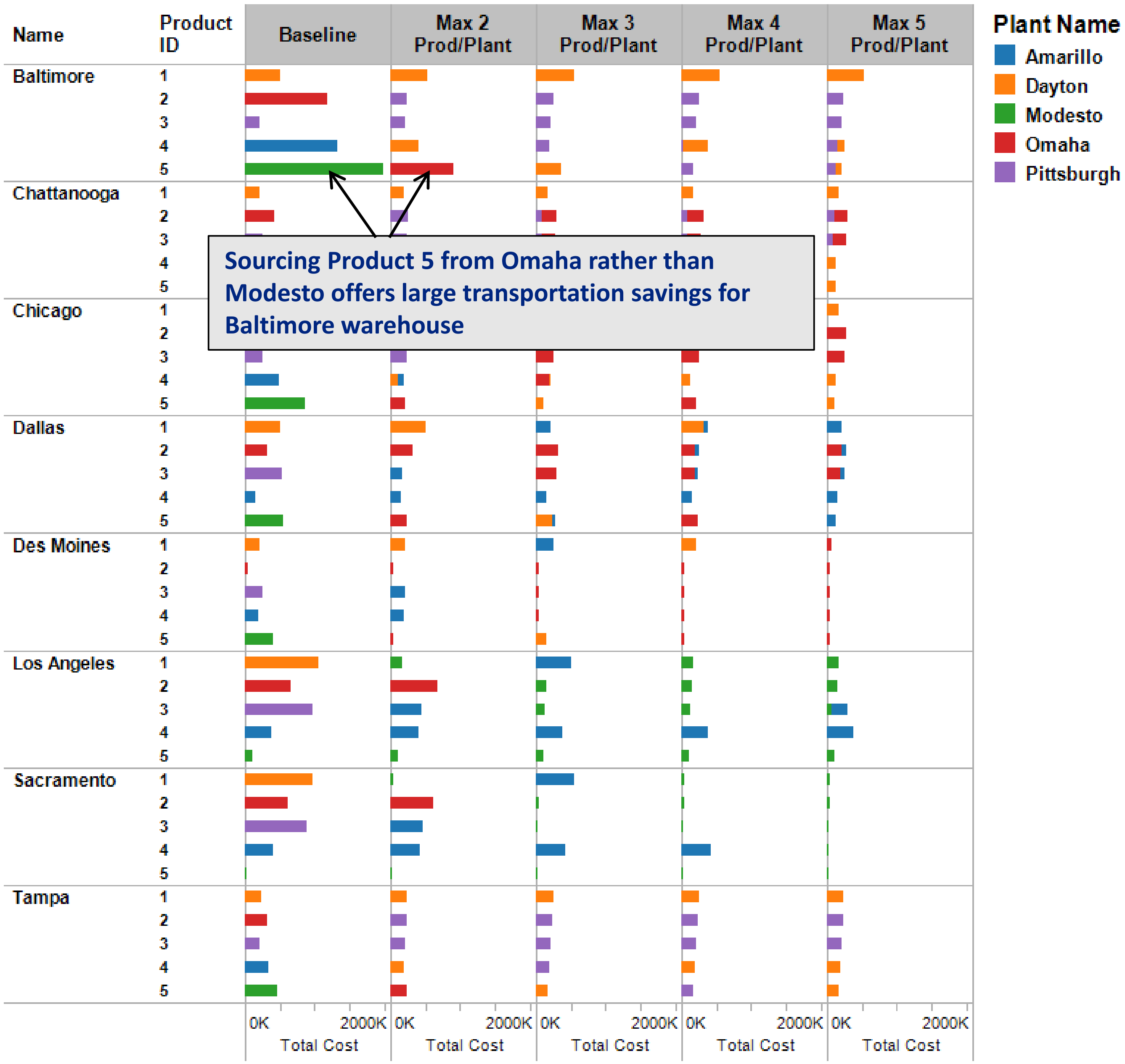
Introducing Manufacturing Flexibility

- To analyze the benefits of adding manufacturing flexibility to the network, the following scenarios were analyzed:
    1. Base Case: Each plant focuses on a single product family
    2. Minimal Flexibility: Each plant can manufacture up to two product families
    3. Average Flexibility: Each plant can manufacture up to three product families
    4. Advanced Flexibility: Each plant can manufacture up to four product families
    5. Full Flexibility: Each plant can manufacture all five product families

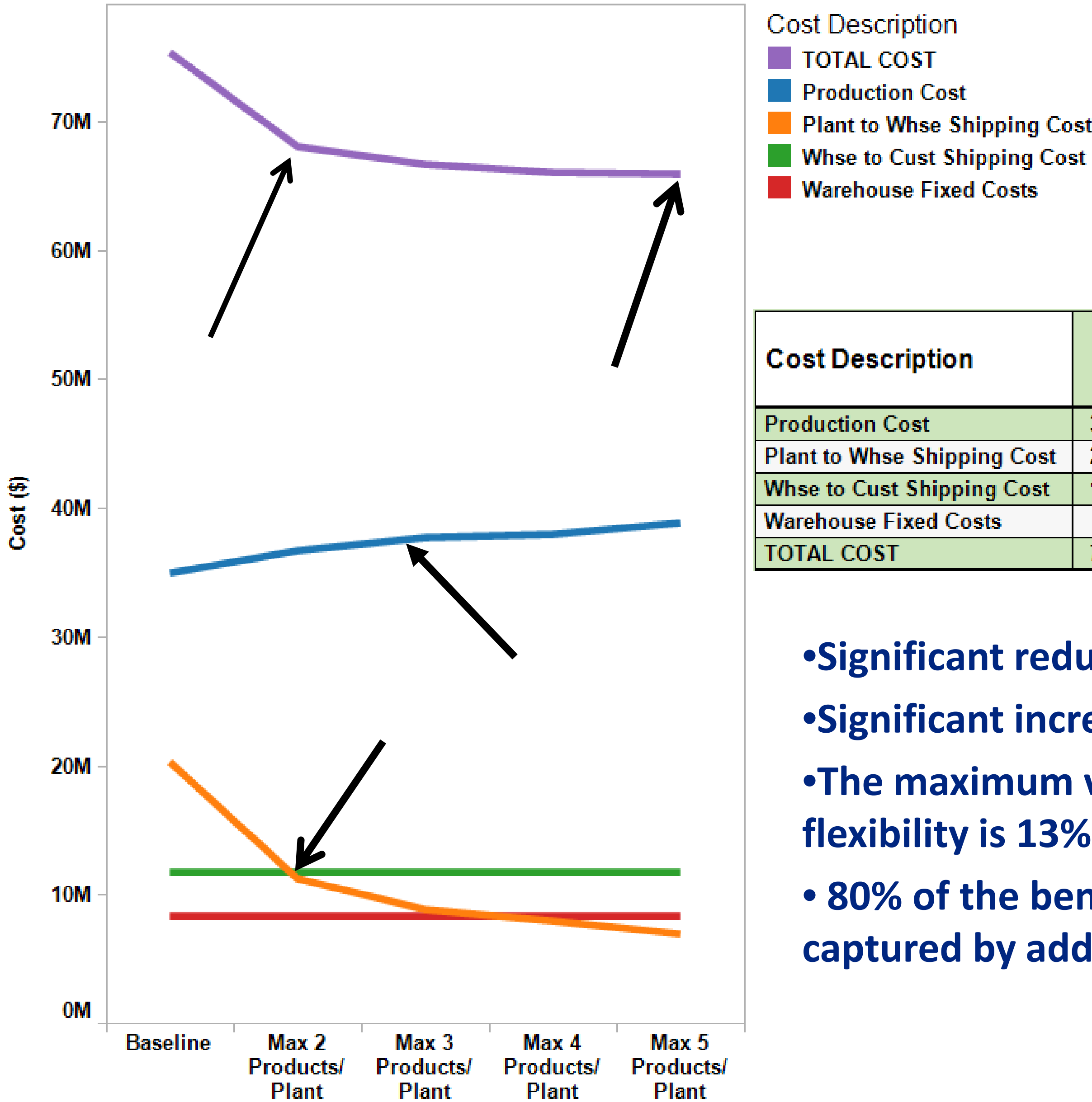
Plant to Warehouse Shipping Comparison



Plant to Warehouse Shipping Comparison



Total Cost Comparison



Cost Description	Baseline	Max 2 Products/ Plant	Max 3 Products/ Plant	Max 4 Products/ Plant	Max 5 Products/ Plant
Production Cost	34,960,649	36,730,087	37,639,959	37,913,955	38,830,279
Plant to Whse Shipping Cost	20,264,858	11,225,563	8,895,809	8,006,541	6,908,562
Whse to Cust Shipping Cost	11,751,467	11,692,662	11,722,858	11,743,225	11,773,756
Warehouse Fixed Costs	8,400,000	8,400,000	8,400,000	8,400,000	8,400,000
TOTAL COST	75,376,974	68,048,313	66,658,625	66,063,721	65,912,597

- **Significant reduction in transportation cost**
- **Significant increase in manufacturing cost**
- **The maximum variable cost savings with full flexibility is 13%**
- **80% of the benefits of full flexibility is captured by adding minimal flexibility**

Impact of Changes in Demand Volume

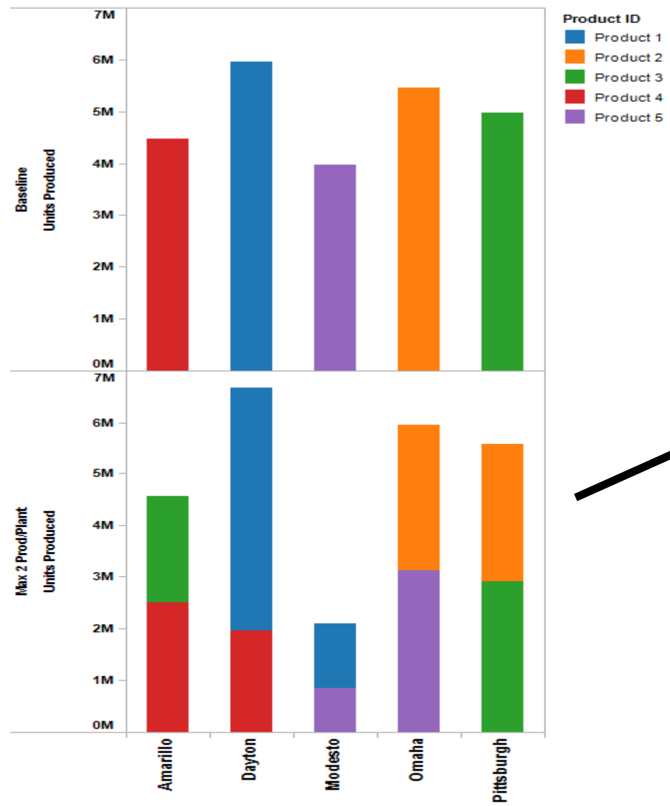
Sensitivity analysis to changes above and below the forecast:

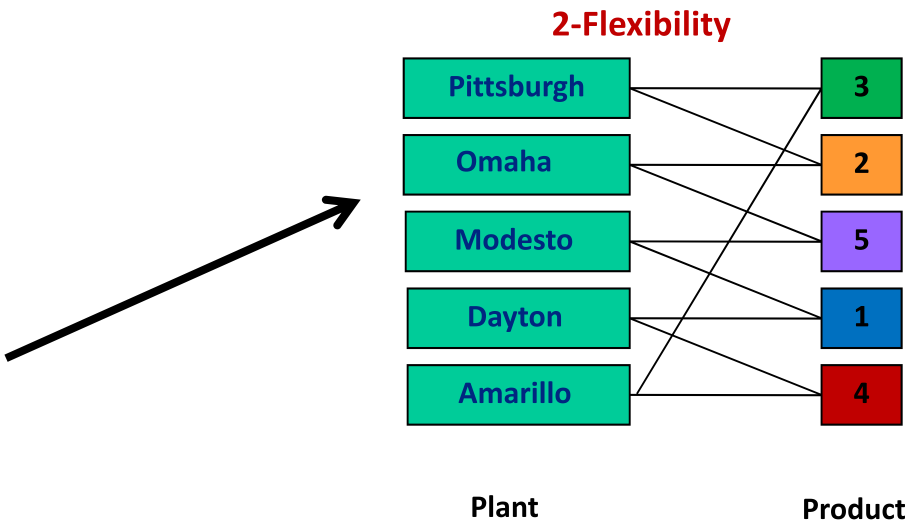
1. **Growth for leading products (1 & 2) by 25% and slight decrease in demand for other products (5%).**
2. **Growth for the lower volume products (4 & 5) by 35% and slight decrease in demand for other products (5%).**
3. **Growth of demand for the high potential product (3) by 100% and slight decrease in demand for other products (10%).**

Impact of Changes in Demand Volume

	Design	Demand Satisfied	Shortfall	Cost/ Unit	Avg Plant Utilization
Demand Scenario 1	Baseline	25,520,991	1,505,542	$ 2.94	91%
	Min Flexibility	27,026,533	0	$ 2.75	97%
Demand Scenario 2	Baseline	25,019,486	1,957,403	$ 2.99	91%
	Min Flexibility	26,976,889	0	$ 2.75	96%
Demand Scenario 3	Baseline	23,440,773	4,380,684	$ 2.93	84%
	Min Flexibility	27,777,777	43,680	$ 2.79	100%

Why 2-Flexibility is so powerful?

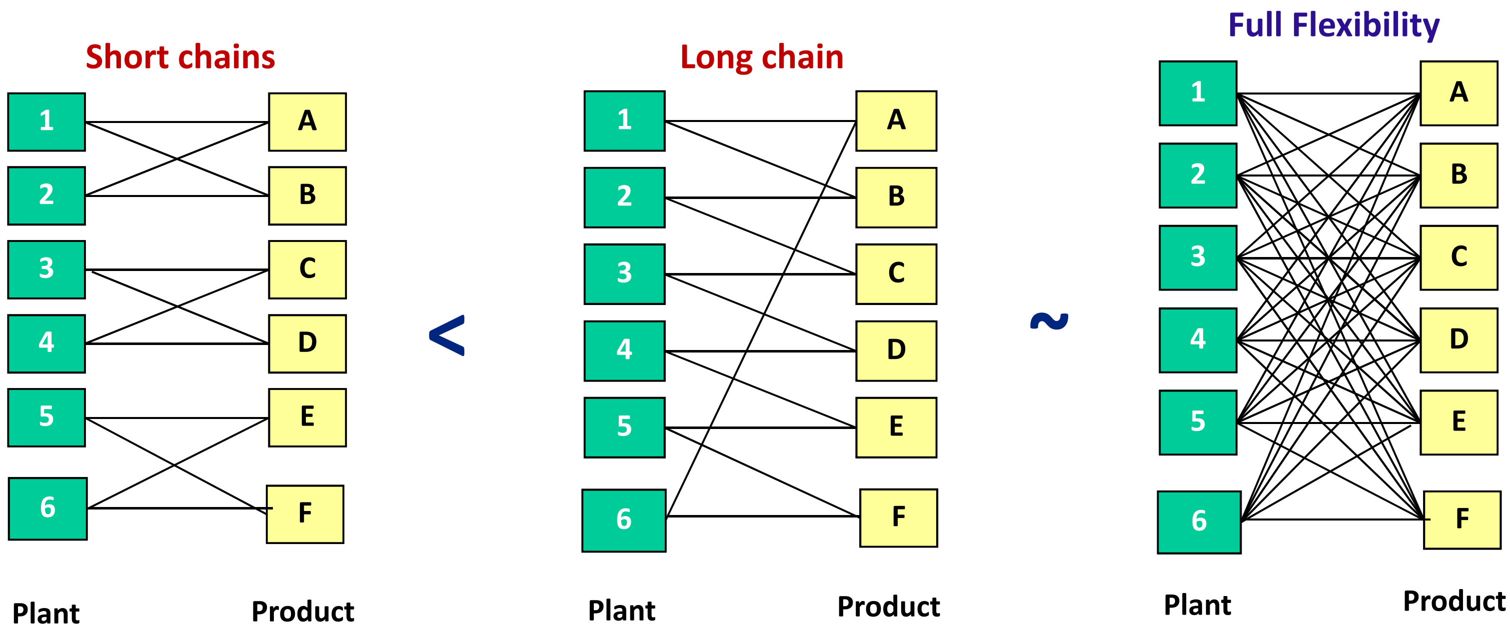




- 2 Flexibility provides the benefits of full flexibility through the creation of a chain

Chaining Strategy (Jordan & Graves 1995)

- **Focus: maximize the amount of demand satisfied**
- **Simulation study**



Two Research Streams on Flexibility

- **Optimal mix between dedicated and full flexibility resources**
  - **Examples:** Fine & Freund, 1990; van Mieghem, 1998; Bish & Wang, 2004
  - **Limitations:** Significant investments are required
- **Limited degree of flexibility**
  - **Empirical Studies:** Jordan & Graves 1995; Graves & Tomlin 2003; Hopp, Tekin & Van Oyen 2004; Iravani, Van Oyen & Sims 2005; Deng & Shen 2009;
  - **Analytical/Theoretical Studies:** Aksin & Karaesmen 2007; Chou et al. 2010; Chou et al. 2011; Simchi-Levi & Wei 2011

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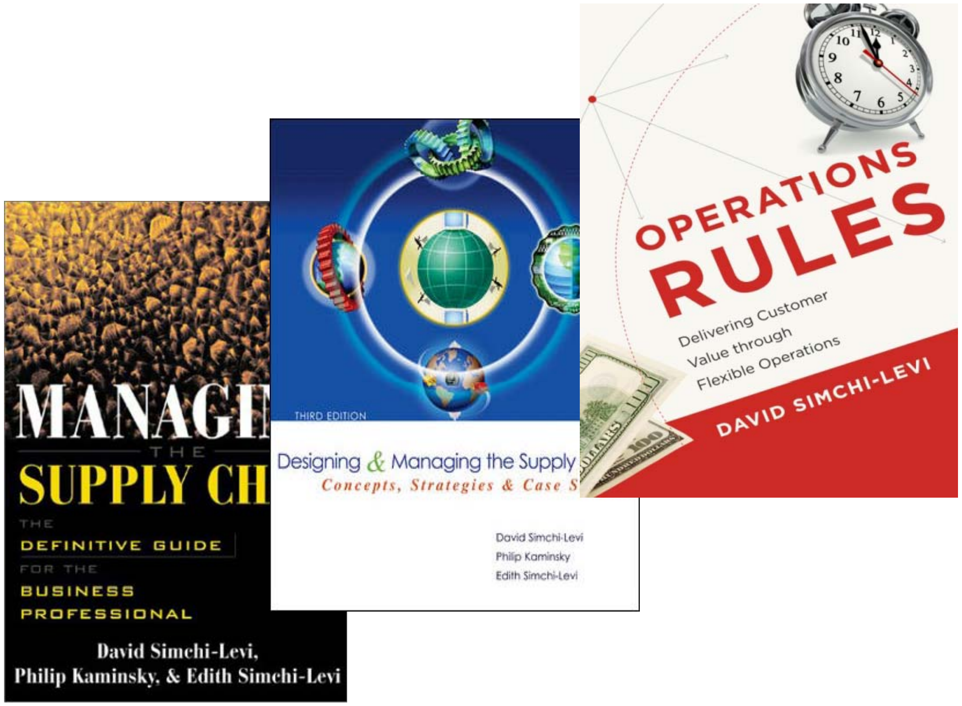
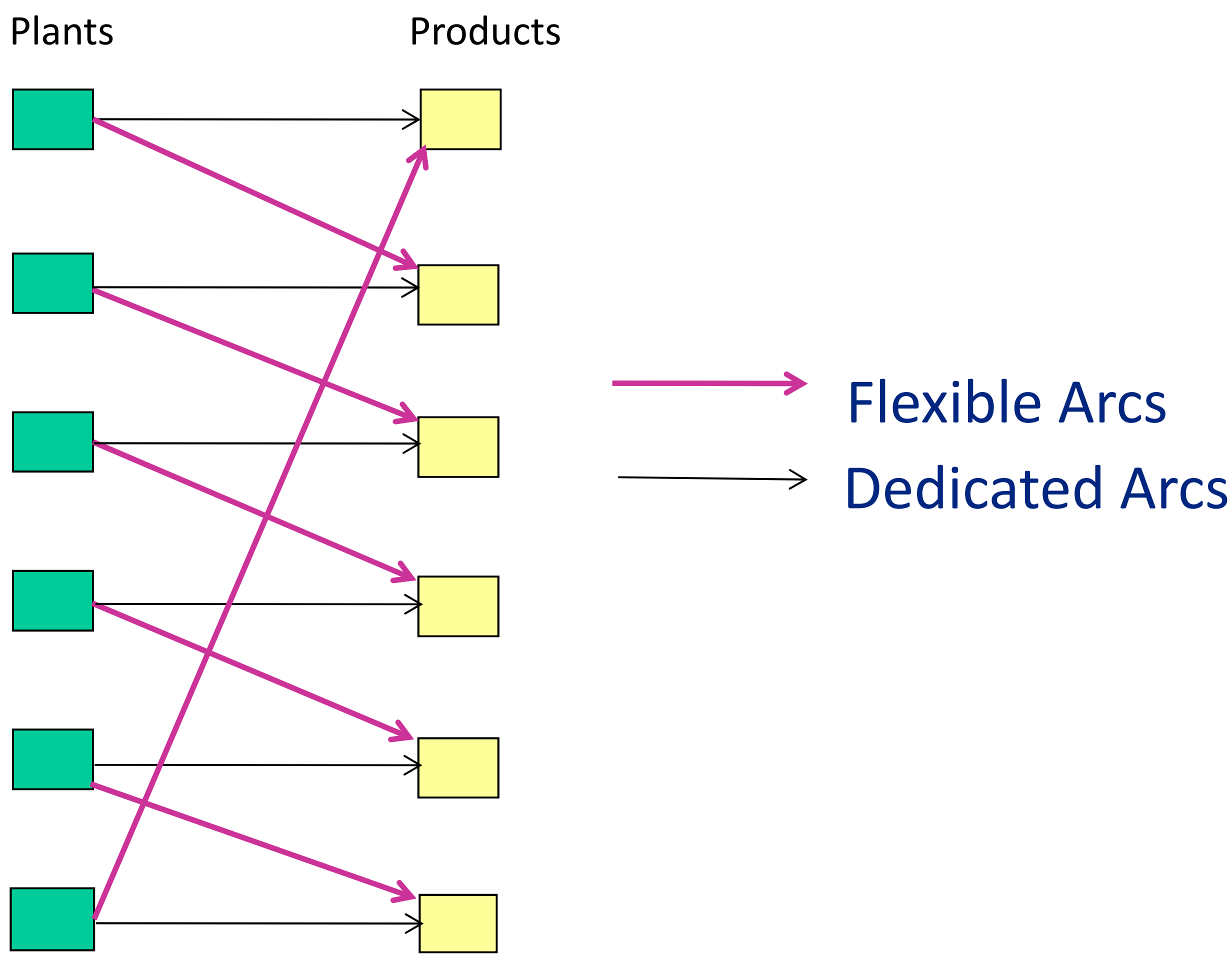


The Model: Flexible and Dedicated Arcs

- n plants
- n products
- Plant capacity = 1
- Product demand I.I.D with mean 1



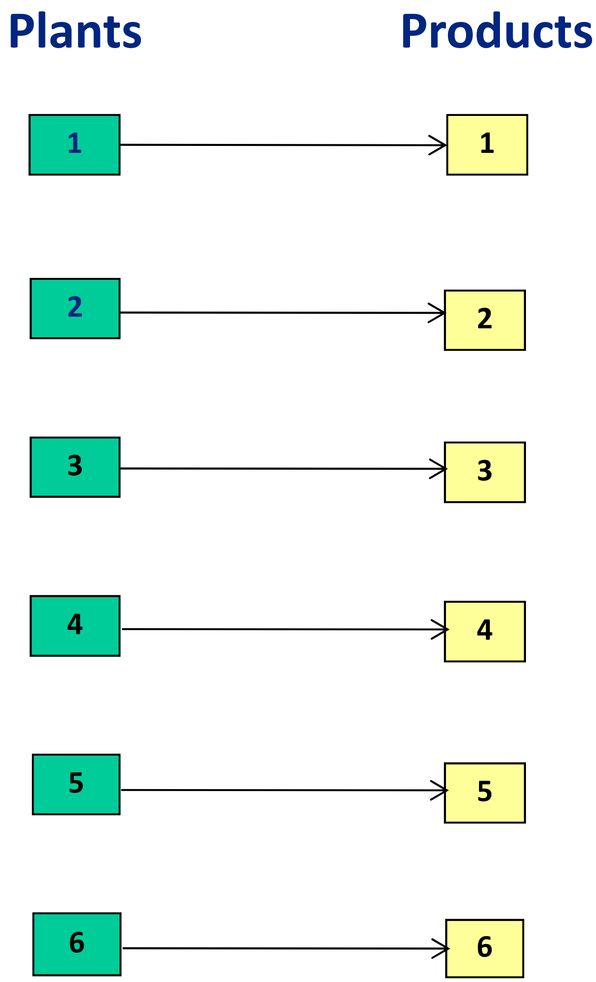
Model and the Performance Metric

For a fixed demand instance **D**, the sales for flexibility design A, P(**D**, A), is:

$$
\begin{aligned}
P(\mathbf{D}, A) = \max \quad & \sum_{1 \le i,j \le n} f_{ij} \\
\text{s.t.} \quad & \sum_{i=1}^{n} f_{ij} \le D_j, \ \forall 1 \le j \le n \\
& \sum_{j=1}^{n} f_{ij} \le 1, \ \forall 1 \le i \le n \\
& 0 \le f_{ij}, \forall (i,j) \in A \\
& f_{ij} = 0, \forall (i,j) \notin A
\end{aligned}
$$

Given random demand **D**, the performance of A is measured by the expected sales of A, E[P(**D**, A)], (or [A])

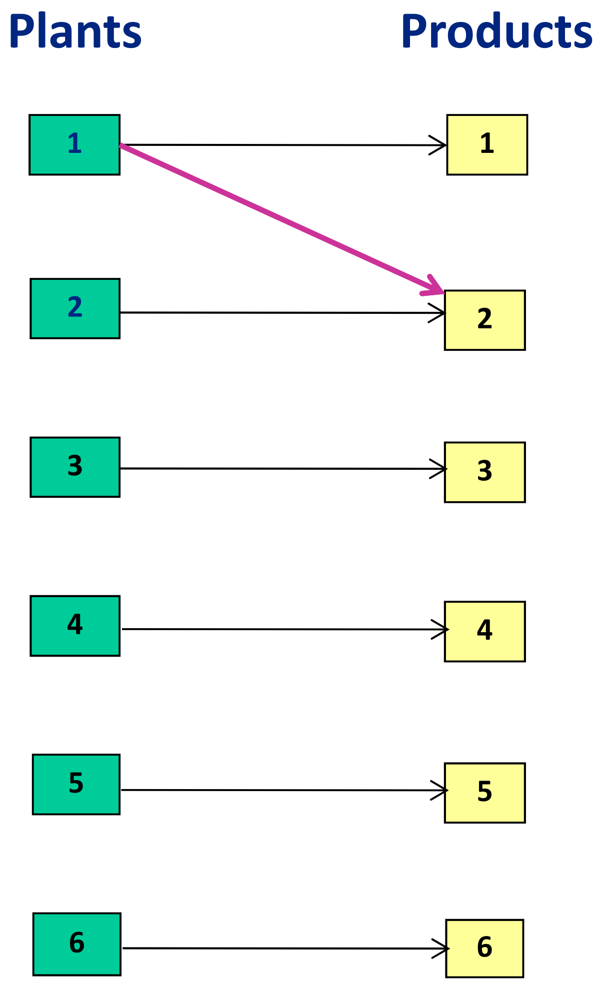
A Motivating Example



Design	Performance	Incr. Performance
Dedicated	**5.6**	

Demand for each product is IID and equals to 0.8, 1 or 1.2 with equal probabilities

A Motivating Example



Design	Performance	Incr. Performance
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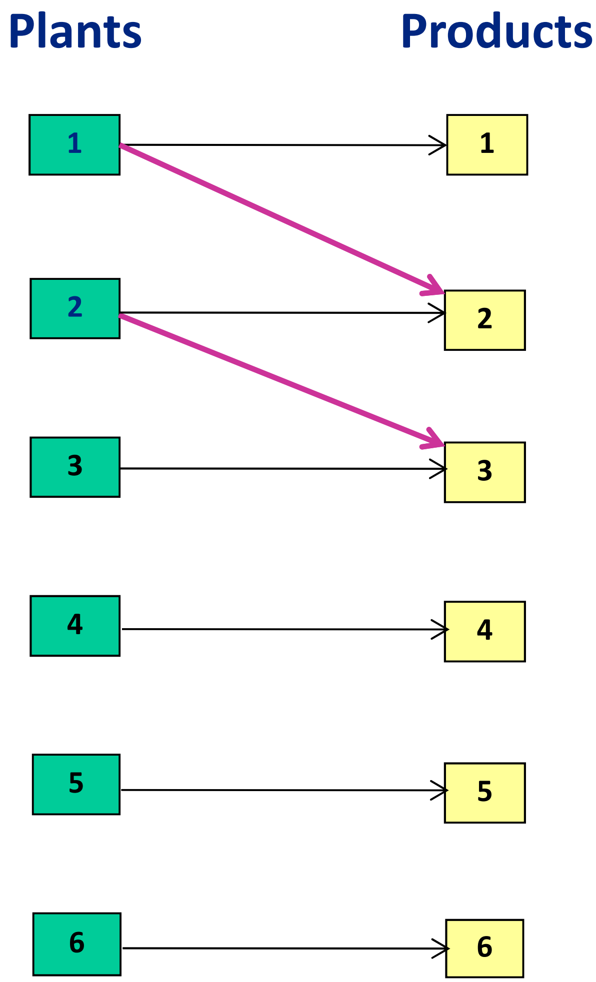
Add (1,2)	**5.622**	**0.022**

A Motivating Example



Design	Performance	Incr. Performance
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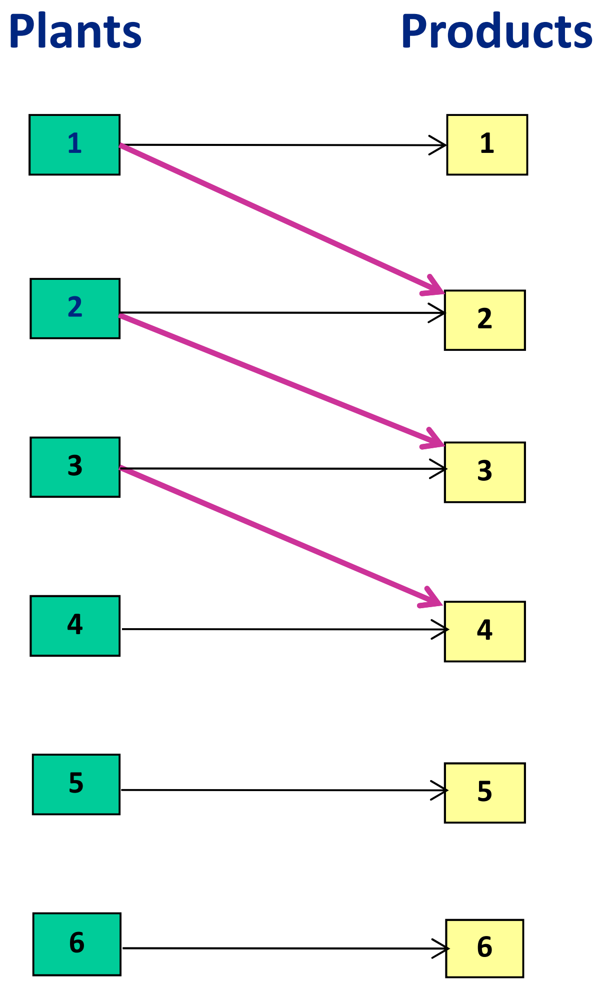
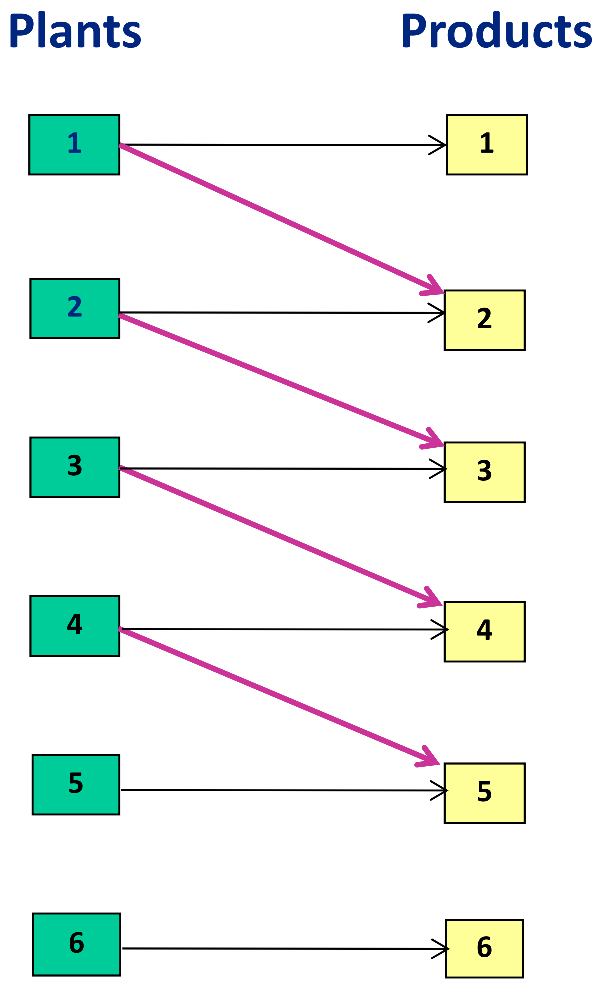
Add (1,2)	**5.622**	**0.022**
Add (2,3)	**5.652**	**0.030**

A Motivating Example



Design	Performance	Incr. Performance
Dedicated	**5.6**	
Add (1,2)	**5.622**	**0.022**
Add (2,3)	**5.652**	**0.030**
Add (3,4)	**5.686**	**0.035**

A Motivating Example



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Add (4,5)	**5.724**	**0.0379**

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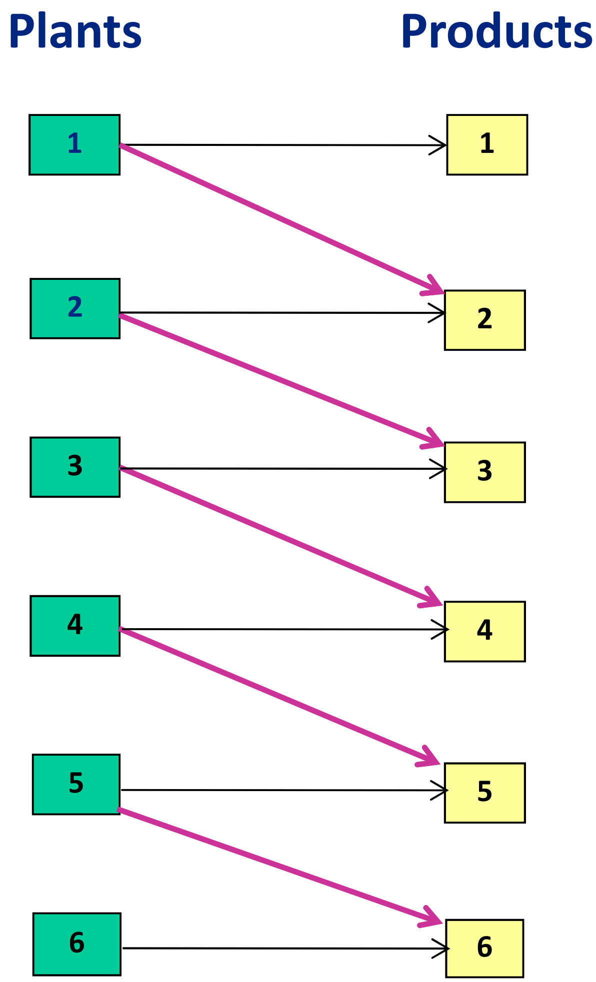

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Add (5,6)	**5.765**	**0.0403**

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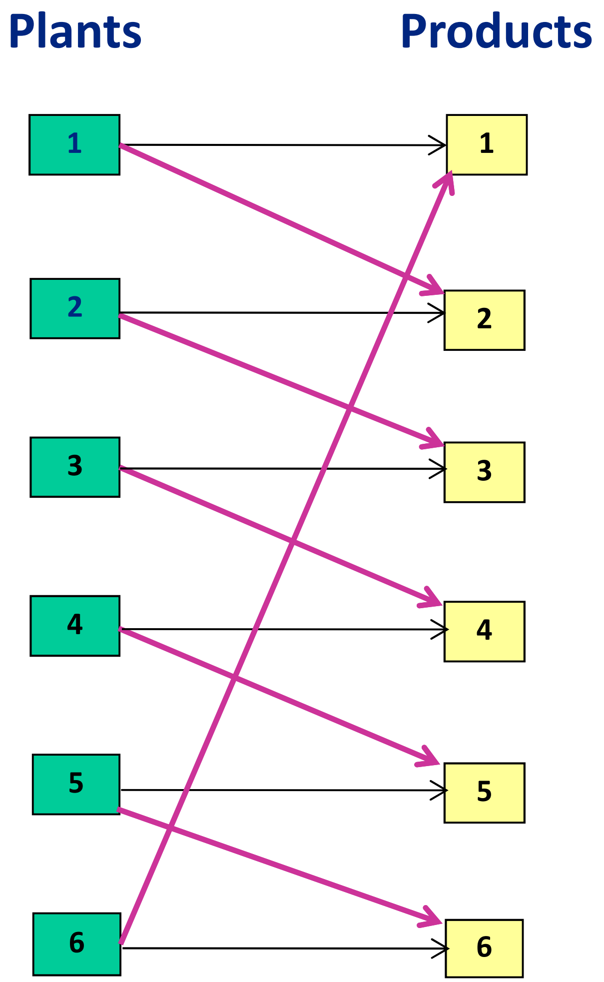

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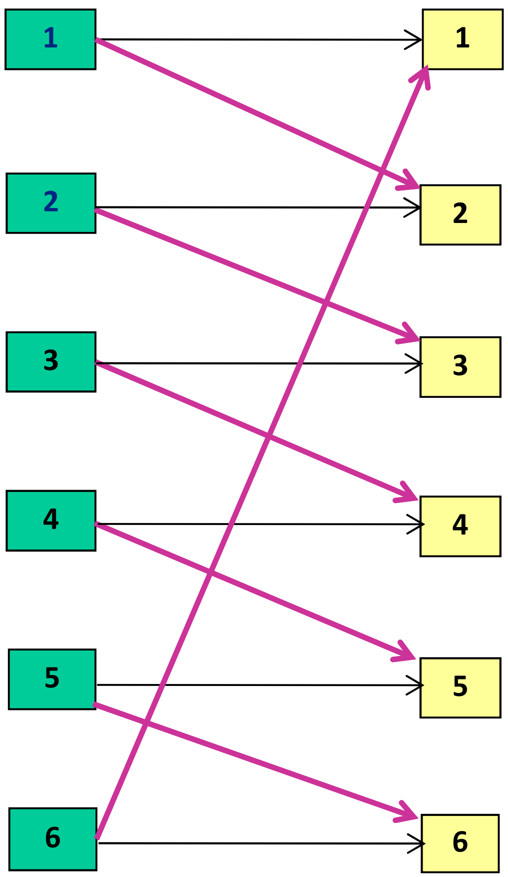
Add (5,6)	**5.765**	**0.0403**
Add (6,1)	**5.842**	**0.077**

A Motivating Example

Observed by for example Hopp et al. (2004), Graves (2008)



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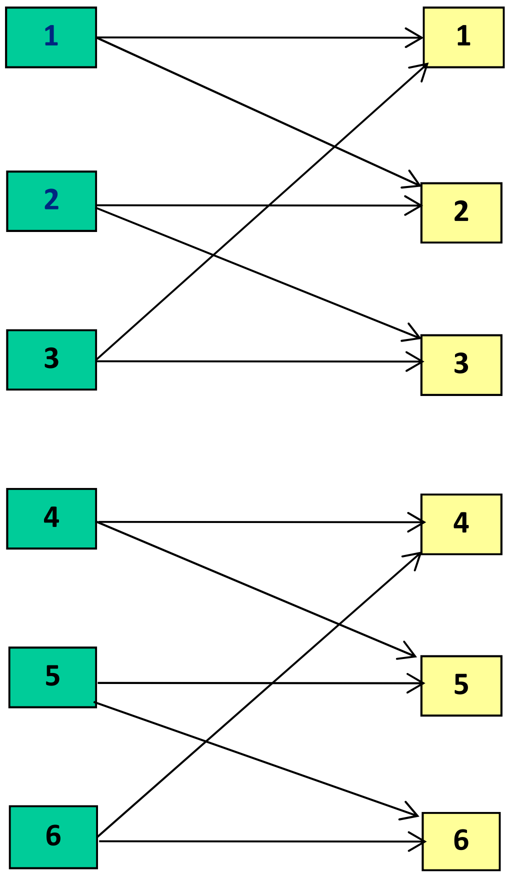
Add (5,6)	**5.765**	**0.0403**
Add (6,1)	**5.842**	**0.077**

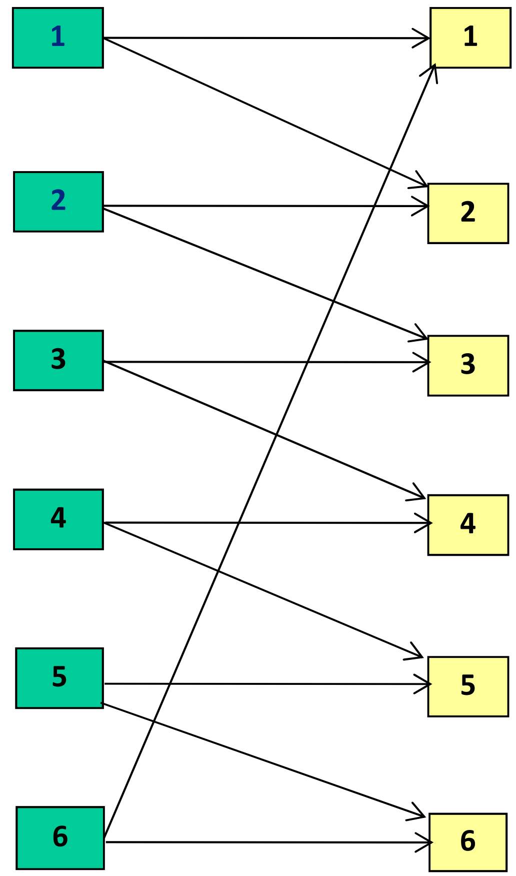
Note that the incremental benefit is increasing, and the largest increase occurs at the *last arc*.

Motivating Examples (Cont.)



Performance: 5.770

$\leq$



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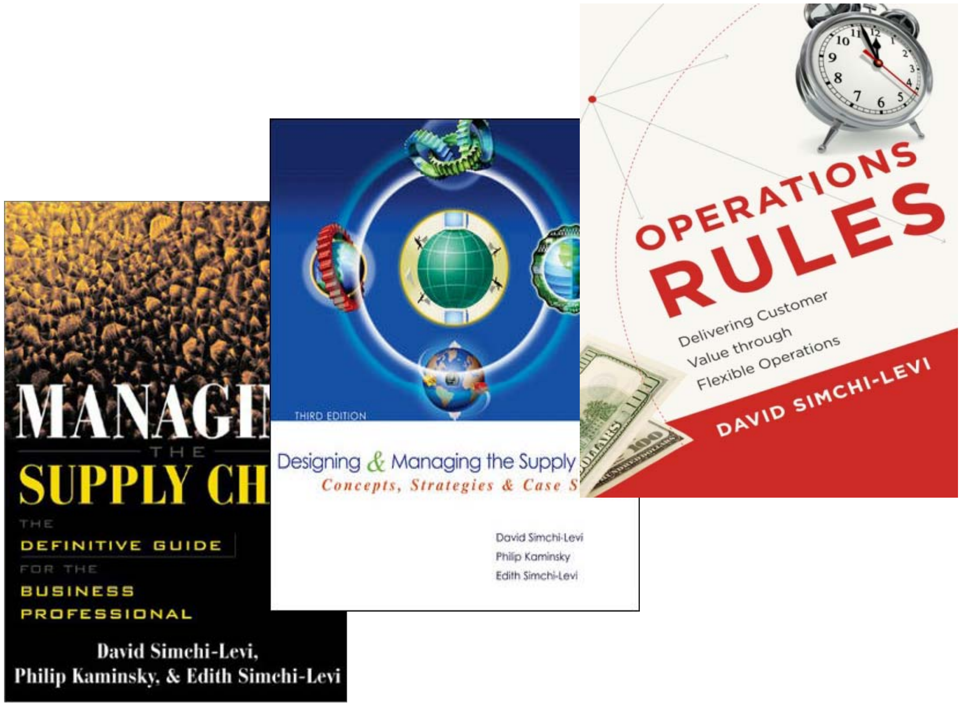


Given Demand, a Long Chain and two Flexible Arcs α and β

$$
\begin{aligned}
P(u_\alpha, u_\beta, \mathbf{D}) = \max \quad & \sum_{i,j} f_{ij} \\
\text{s.t.} \quad & \sum_{i} f_{ij} \leq D_j, \\
& \sum_{j} f_{ij} \leq 1 \\
& f_\alpha \leq u_\alpha, \\
& f_\beta \leq u_\beta, \\
& f_{ij} \geq 0, \forall (i,j) \in LC \\
& \mathbf{f} \in \mathbb{R}^{|LC|}
\end{aligned}
$$

where LC is the long-chain we described previously, while α and β are distinct arcs in the long-chain.

Supermodularity of Flexible Arcs in a Long-chain

Theorem 1

P(u_α, u_β, **D**) is supermodular for any flexible arcs α and β. That is,

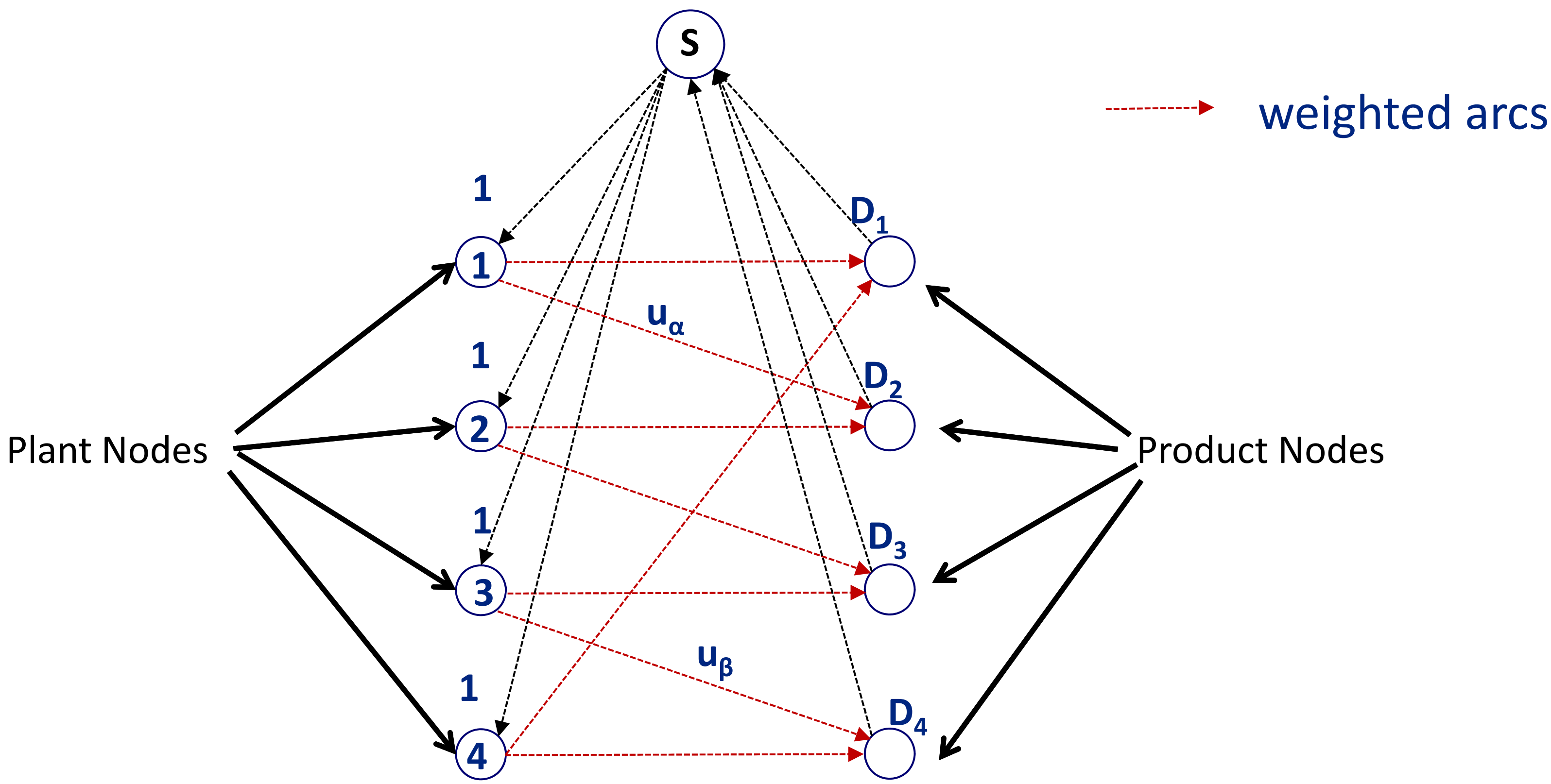
$$\mathrm{P}(\max(u_\alpha^1, u_\alpha^2), \max(u_\beta^1, u_\beta^2), \mathbf{D}) + \mathrm{P}(\min(u_\alpha^1, u_\alpha^2), \min(u_\beta^1, u_\beta^2), \mathbf{D})$$

$$\geq \mathrm{P}(u_\alpha^1, u_\beta^1, \mathbf{D}) + \mathrm{P}(u_\alpha^2, u_\beta^2, \mathbf{D})$$

for any real numbers $u_\alpha^1, u_\alpha^2, u_\beta^1, u_\beta^2$.

$P(u_\alpha,u_\beta,D)$ as a Maximum Weight Circulation Problem

Consider the following maximum weight circulation problem:



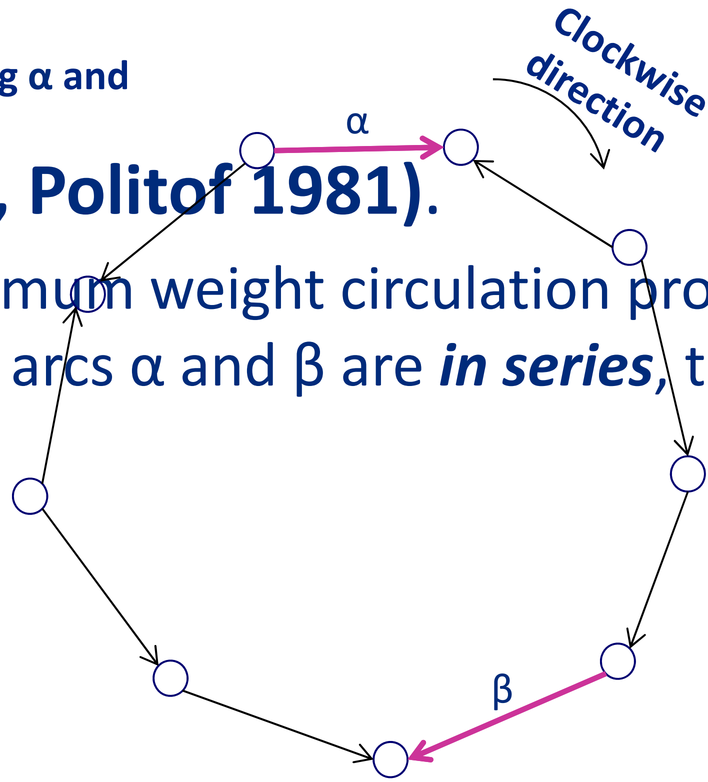
This maximum weight circulation problem is equivalent to our original formulation of $P(u_\alpha,u_\beta,\mathbf{D})$.

Maximum Weight Circulation Problem

Definition.

In a directed graph, arcs α and β are said to be ***in series*** if there is no simple undirected cycle in which α and β have opposite directions.

For every cycle containing α and β, we have:

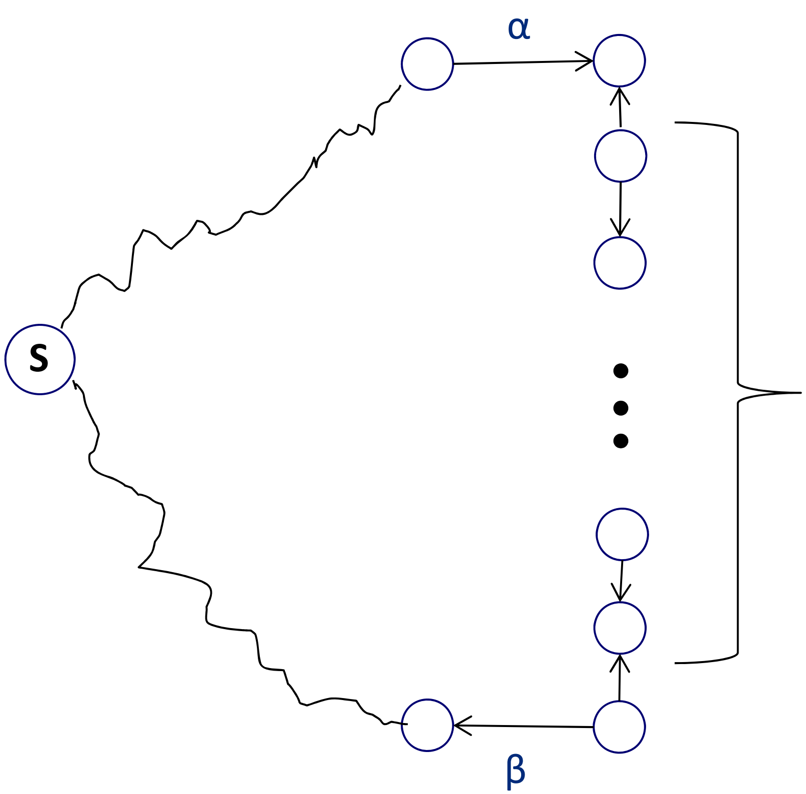


Theorem (Gale, Politof 1981).

Consider the maximum weight circulation problem correspond to $P(u_\alpha,u_\beta,\mathbf{D})$. If arcs α and β are ***in series***, then $P(u_\alpha,u_\beta,\mathbf{D})$ is supermodular.

Sketch of the Proof for Theorem 1

Fix any two flexible arcs α and β in the long-chain. Consider any undirected cycle C which contains both α and β, if C does not contain S, the result is trivial; otherwise,



2k+1 arcs, directions of the arcs always alternating

Supermodularity of Flexible Arcs in a Long-chain

Theorem 1

P(u_α, u_β, **D**) is supermodular for any flexible arcs α and β. That is,

P(max(u_α^1, u_α^2), max(u_β^1, u_β^2), **D**)+P(min(u_α^1, u_α^2), min(u_β^1, u_β^2), **D**)

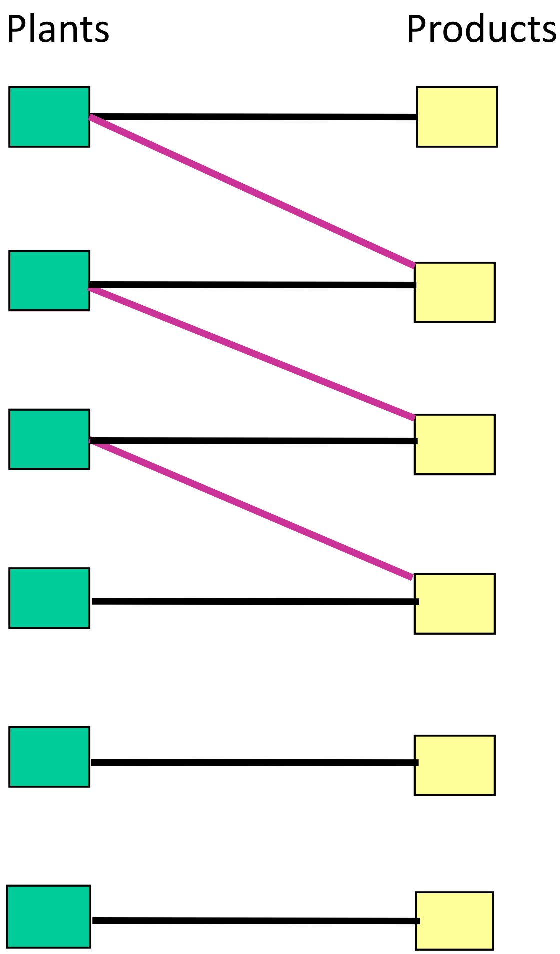
≥ P(u_α^1, u_β^1, **D**) + P(u_α^2, u_β^2, **D**)

for any real numbers u_α^1, u_α^2, u_β^1, u_β^2.

Corollary 1

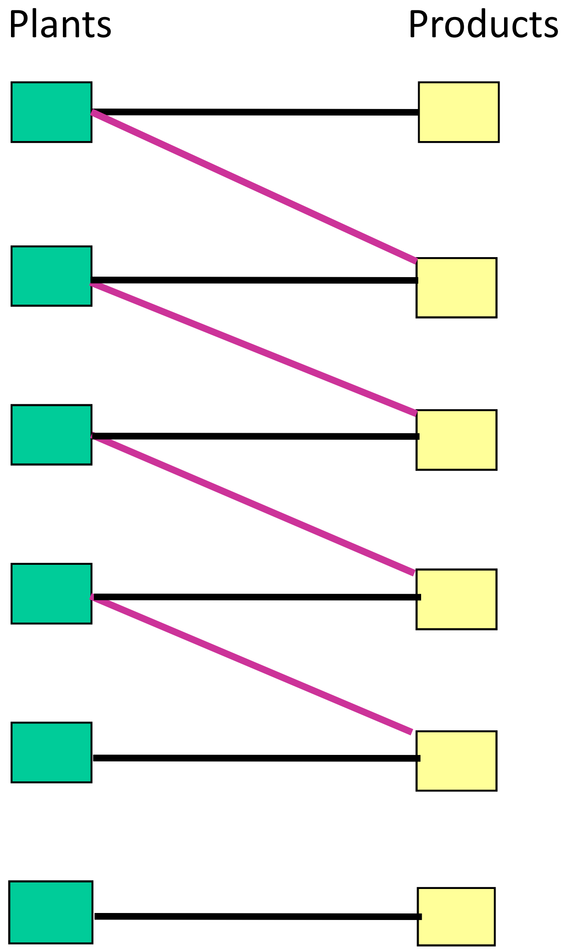
E[P(u_α, u_β, **D**)]is supermodular for any flexible arcs α and β.

Define the Construction of a Long-Chain



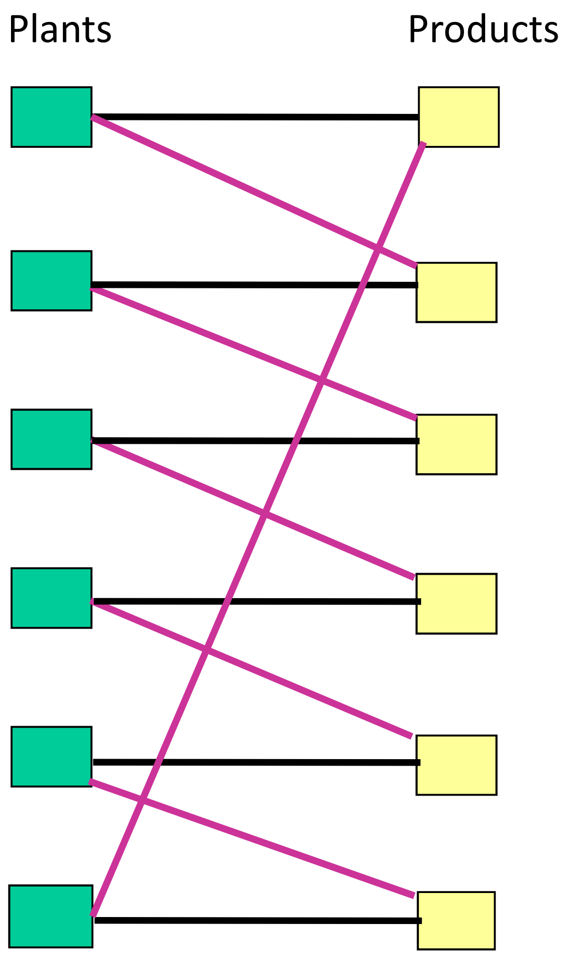
$L_{3,6}$

Define the Construction of a Long-Chain



$L_{4,6}$

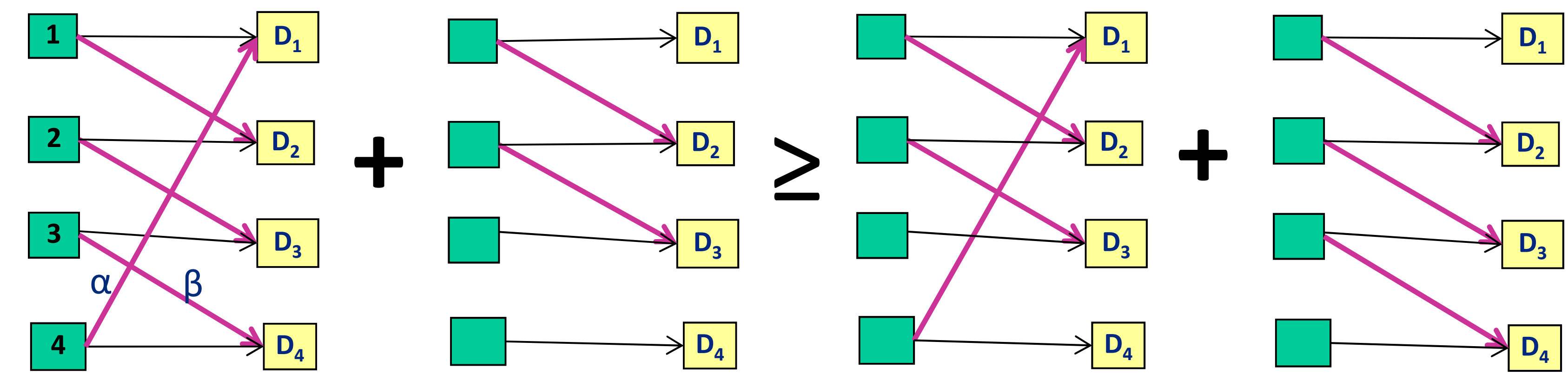
Define the Construction of a Long-Chain



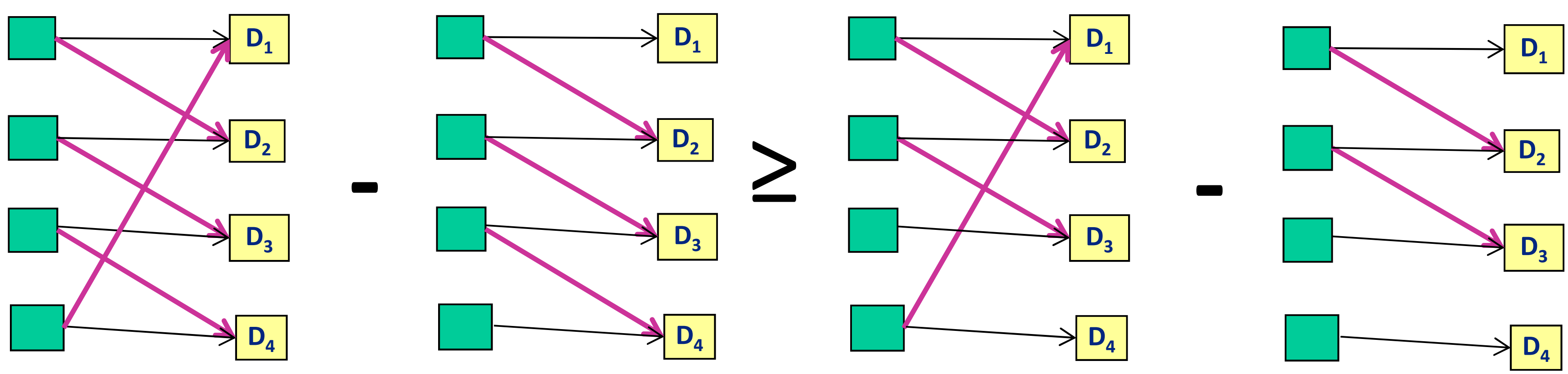
$L_{6,6}$

How supermodulrity explains the power of the Long Chain?

By Theorem 1 we have:



With $u^1_\alpha=1$, $u^1_\beta=0$ and $u^2_\alpha=0$, $u^2_\beta=1$



The Power of the Long Chain

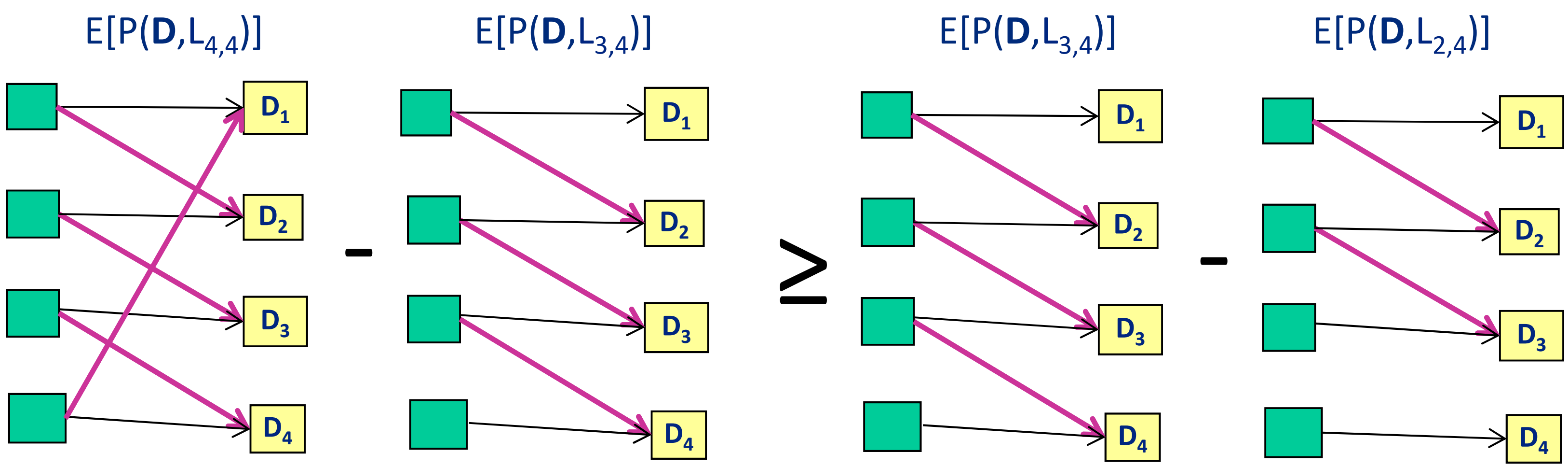
Corollary 2

Suppose the demand for each product is IID, then

$E[P(\mathbf{D}, L_{k+1,n})] - E[P(\mathbf{D}, L_{k,n})] \geq E[P(\mathbf{D}, L_{k,n})] - E[P(\mathbf{D}, L_{k-1,n})]$

for any $1 \leq k \leq n-1$.

For example, in expectation, we have



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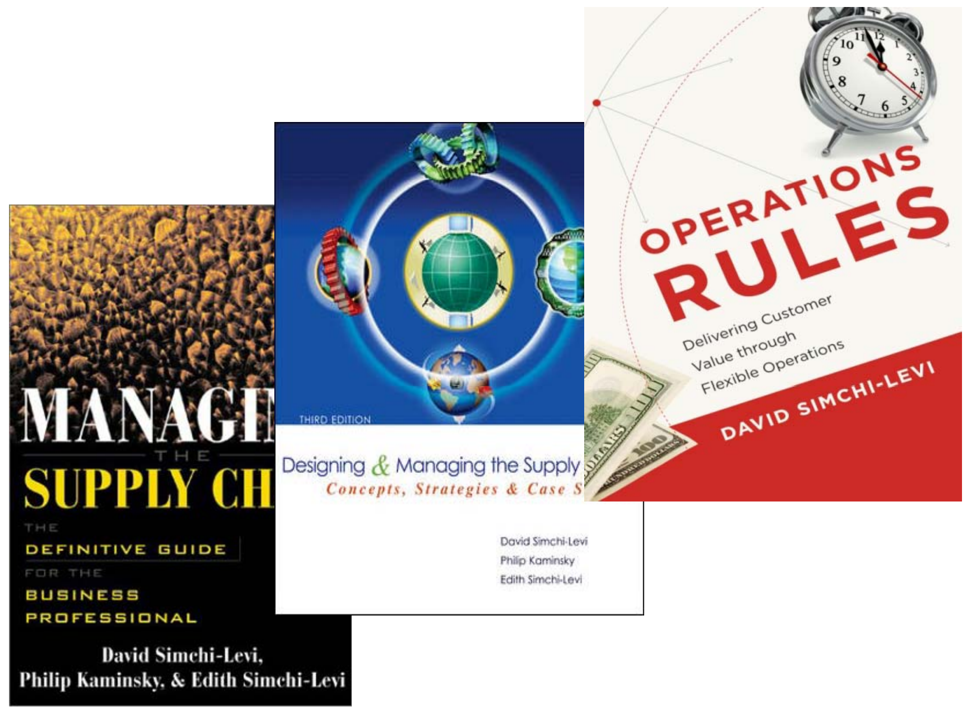


Characterizing the Sales of the Long Chain

Theorem 2 (Characterizing the Sales of the Long Chain)

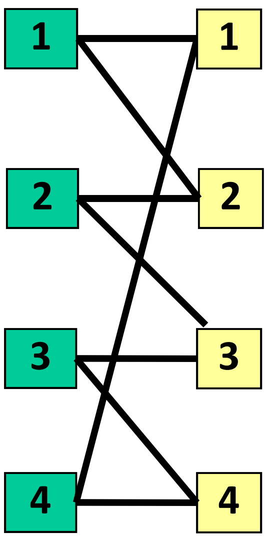
In a system of n product/plant with a fixed demand instance **D**,

$$P(\mathbf{D}, LC) = \sum_{i=1}^{n} \left(P(\mathbf{D}, LC/\{\alpha_i\}) - P(\mathbf{D}, LC/\{\alpha_i, \alpha_{i-1}, \beta_i\})\right)$$

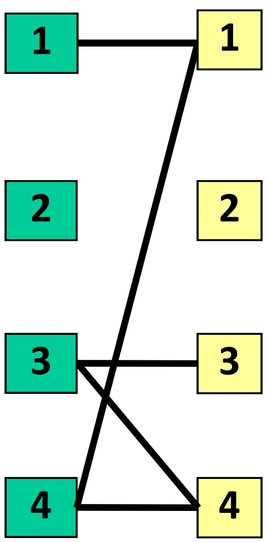
where α_i=(i,i+1) for i=1,…,n-1, α_n=(n,1) and β_i=(i,i) for i=1,..n.

Example: For n =4, i=2

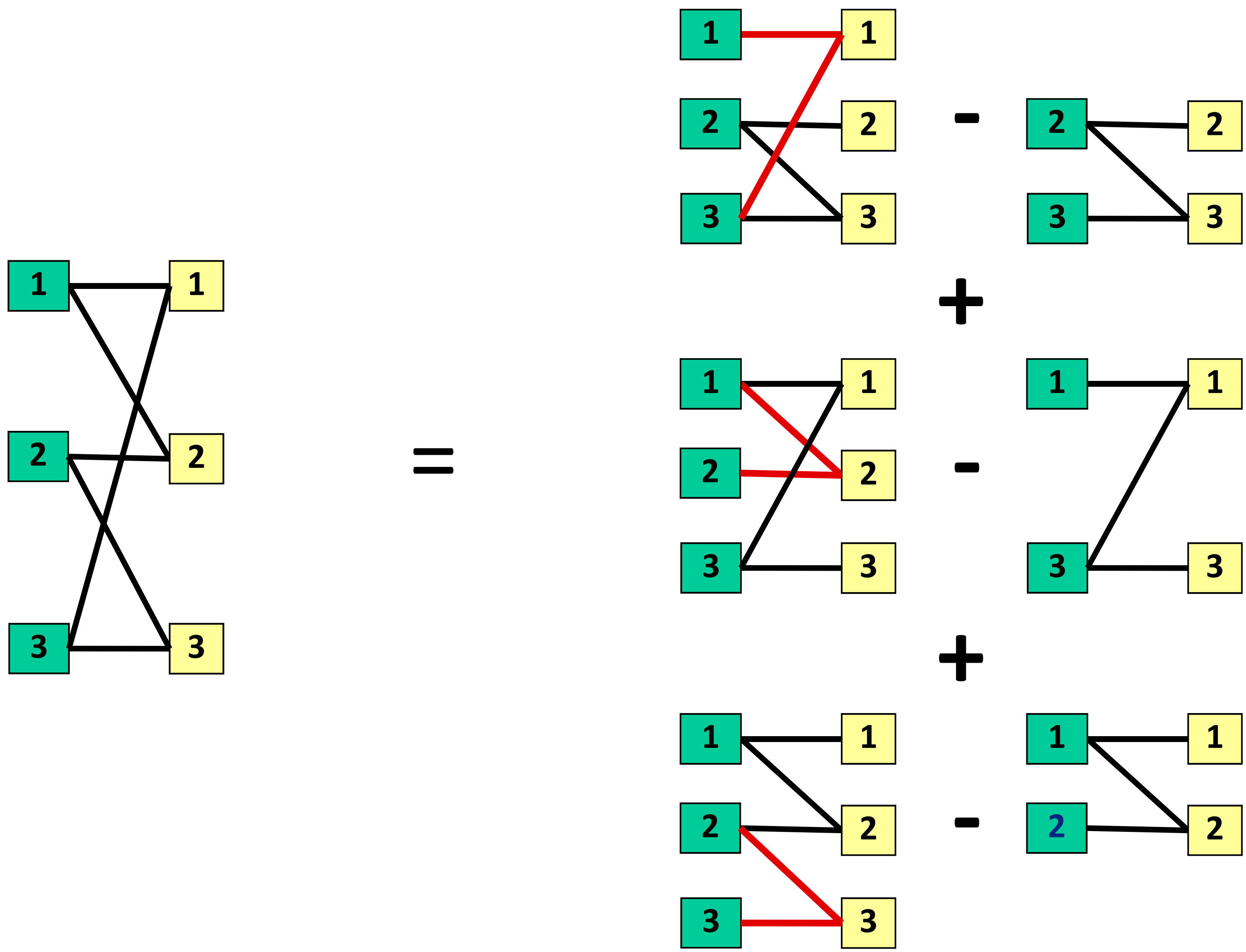
P(**D**, LC/{α_i})



P(**D**, LC/{α_i, α_{i-1}, β_i})



Illustrating the Characterization



The ``Dummy'' Arc in Long Chain

Lemma 1

Suppose P(**D**, LC) = P(**D**, LC /{α_{i*}}) for some i*, then

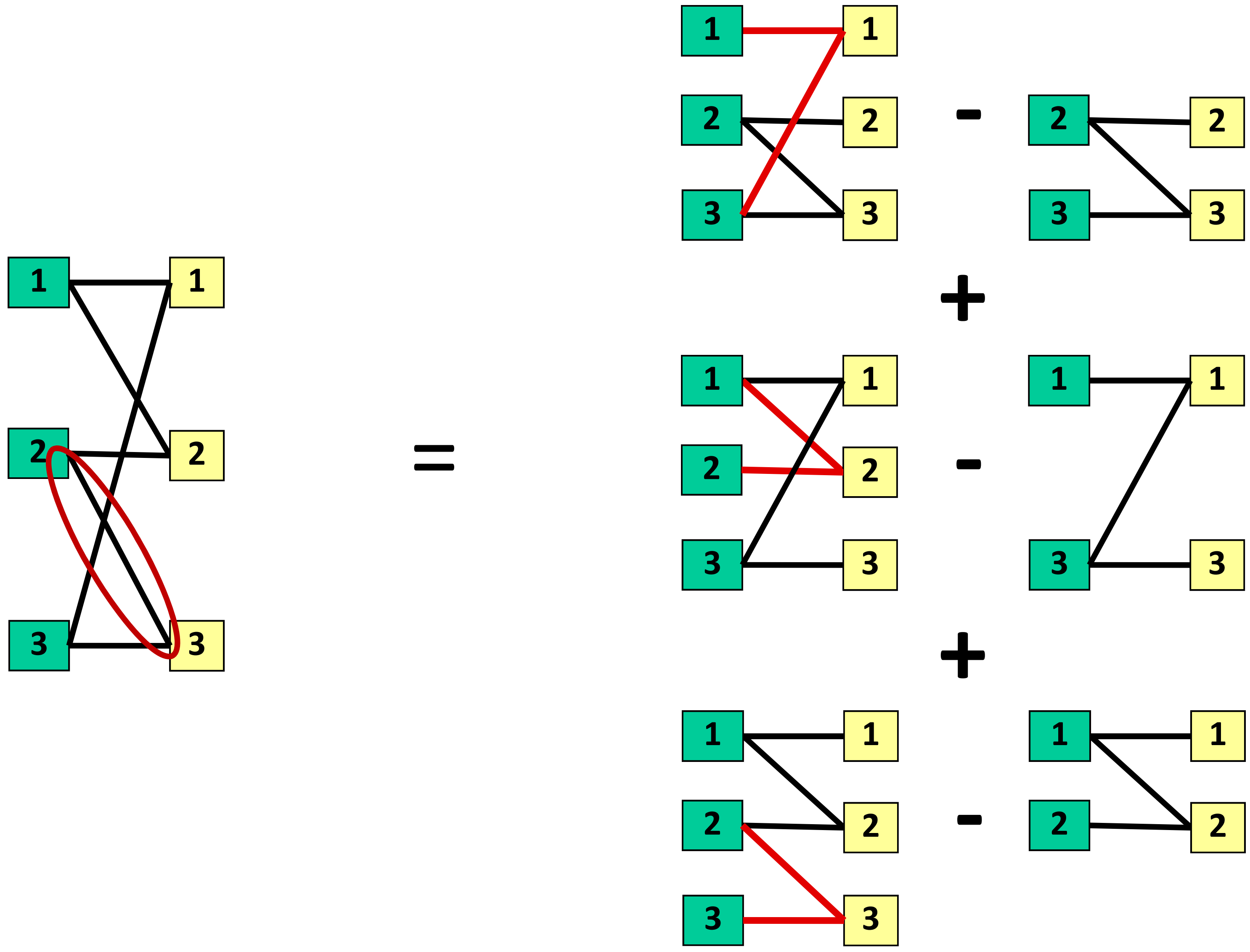
$$P(\mathbf{D}, LC/\{\alpha_i\}) = P(\mathbf{D}, LC/\{\alpha_i, \alpha_{i*}\})$$

$$P(\mathbf{D}, LC/\{\alpha_i, \alpha_{i-1}, \beta_i\}) = P(\mathbf{D}, LC/\{\alpha_i, \alpha_{i-1}, \beta_i, \alpha_{i*}\})$$

where α_i=(i,i+1) for i=1,…,n-1, α_n=(n,1) and β_i=(i,i) for i=1,..n.

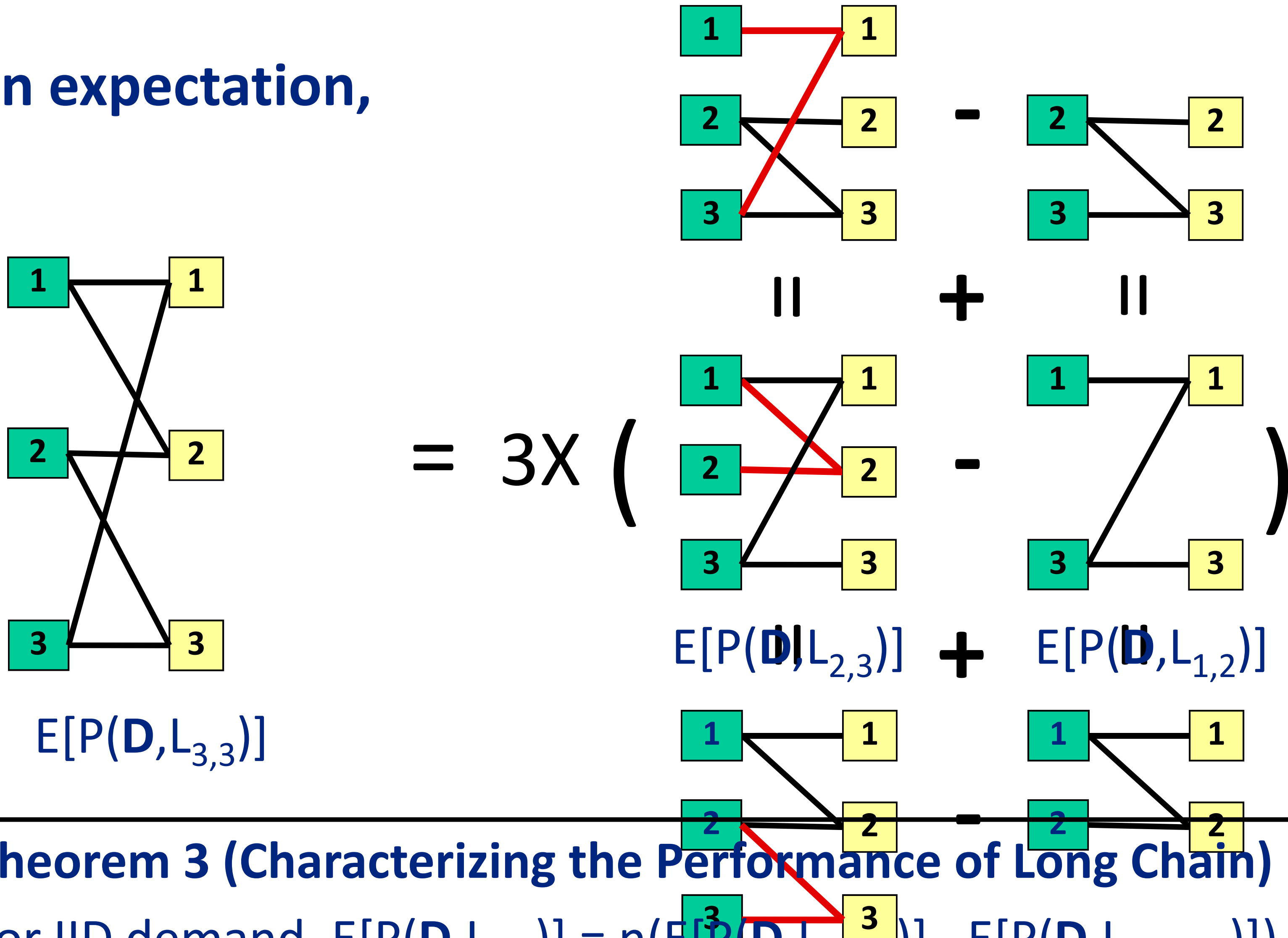
Proof: Lemma 1 follows by the supermodularity result stated in Theorem 1.

“Proof’’ for the Theorem 2



The Characterization In Expectation

In expectation,



Theorem 3 (Characterizing the Performance of Long Chain)

For IID demand, $E[P(\mathbf{D},L_{n,n})] = n(E[P(\mathbf{D},L_{n-1,n})] - E[P(\mathbf{D},L_{n-2,n-1})])$

The “Impact” of Theorem 2

Corollary 3 (Risk Pooling of Long Chain)

Suppose the demand for each product is IID and capacity for each plant is 1, then in a n by n product plant system, we have

$$E[P(\mathbf{D},L_{n+1,n+1})]/(n+1) \geq E[P(\mathbf{D},L_{n,n})]/n$$

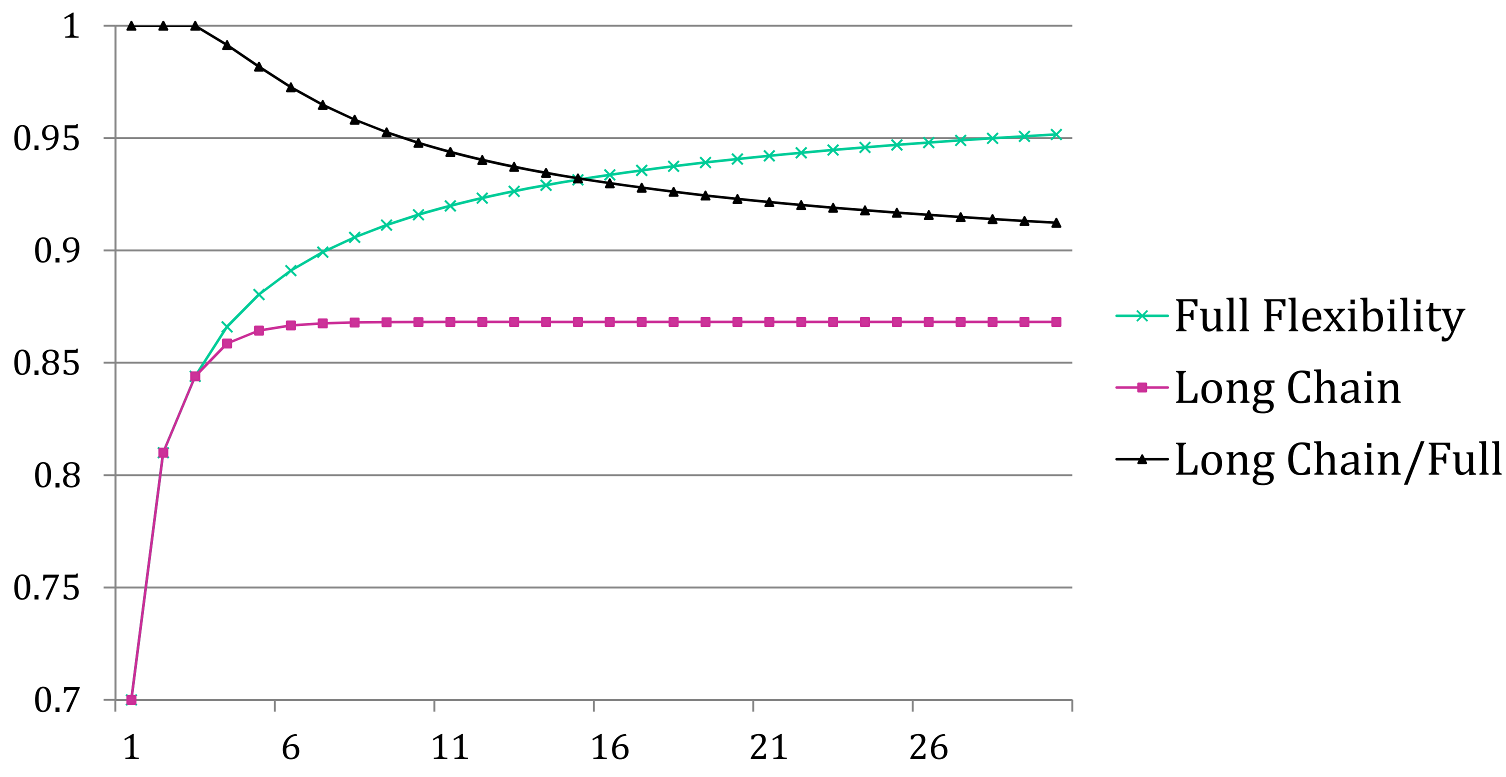
Corollary 4 (Optimality of Long Chain)

In an n product-plant system, if the demand for each product is IID and capacity for each plant is 1, the long chain is always the optimal 2-flexibility system.

Corollary 5 (Computing the Performance of Long Chain)

If D_1 has the support set $\{k/N : k=0,1,2,\ldots\}$, then $E[P(\mathbf{D}, L_{n,n})]$ can be computed with matrix multiplications in $O(nN^2)$ operations.

Plotting the Fill Rate of Long Chain and Full Flexibility



Distribution of D_1 is uniformly distributed on {1/10, 2/10, …, 20/10}.

Risk Pooling of the Long Chain

Corollary 3 (Risk Pooling of Long Chain)

Under IID demand, $E[P(\mathbf{D},L_{n+1,n+1})]/(n+1) \geq E[P(\mathbf{D},L_{n,n})]/n$.

Theorem 4 (Exponential Decrease of Risk Pooling)

Under IID demand,

$\lim_{n\to\infty}\log(E[P(\mathbf{D},L_{n+1,n+1})]/(n+1)-E[P(\mathbf{D},L_{n,n})]/n) \leq nK$,

for some negative constant K.

Theorem 4 implies that in a system with very large size, a collection of several large chains is just as good as a single long chain.

Long Chain vs Full Flexibility

Theorem 5

For IID demand, and any $n \geq 1$,

$$\frac{[F_n]}{n} - \frac{[L_{n,n}]}{n} \leq \frac{[F_{n+1}]}{n+1} - \frac{[L_{n+1,n+1}]}{n+1} \leq 1 - \lim_{k\to\infty} \frac{[L_{k,k}]}{k},$$

where F_n is the full flexibility design of system with size n.

The first inequality of Theorem 4 shows that the gap between the fill rate of full flexibility that of the long chain is increasing.

Interestingly, Chou et al. showed that $\lim_{k\to\infty} \frac{[L_{k,k}]}{k}$ is often close to 1.

Long Chain vs Full Flexibility

Theorem 5

For IID demand, and any $n \geq 1$,

$$\frac{[F_n]}{n} - \frac{[L_{n,n}]}{n} \leq \frac{[F_{n+1}]}{n+1} - \frac{[L_{n+1,n+1}]}{n+1} \leq 1 - \lim_{k\to\infty} \frac{[L_{k,k}]}{k},$$

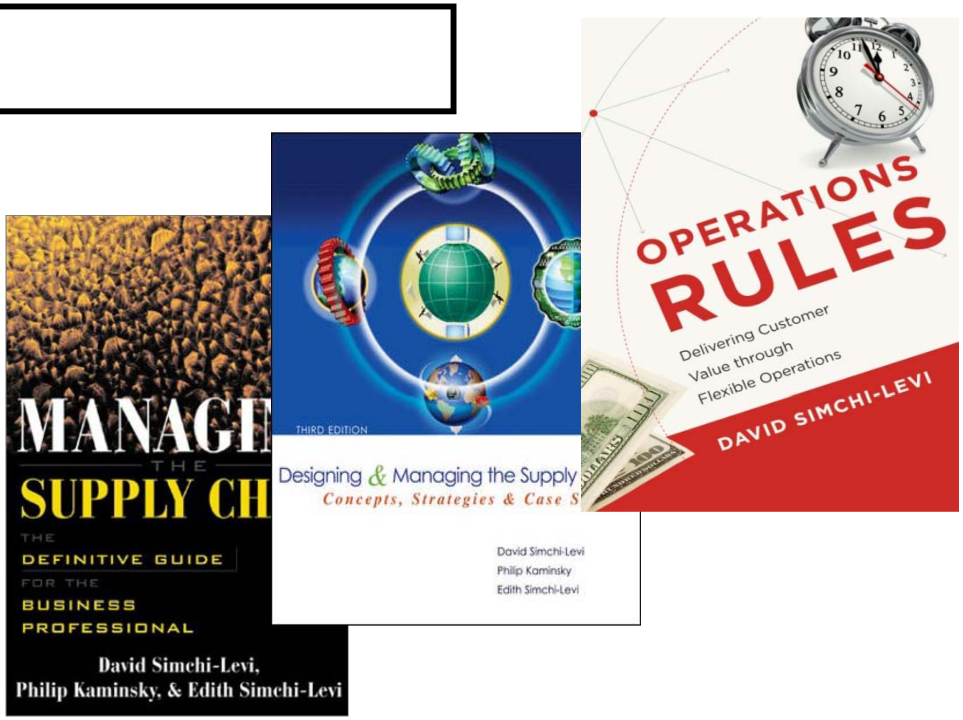
where F_n is the full flexibility design of system with size n.

E.g. when D_1 is normal with mean 1 and std of 0.3, $\lim_{k\to\infty} \frac{[L_{k,k}]}{k} \approx 0.96$.

Then, we have $\frac{[F_n]}{n} - \frac{[L_{n,n}]}{n} \leq 0.04$ for all n, and moreover, we can use Theorem 5 to show that $\frac{[L_{n,n}]}{[F_n]} \geq 0.9568$.

What We'll Cover …

- **Introduction to Flexibility**
- **Model and Motivating Examples**
- **Supermodularity in Long Chains**
- **Additivity in Long Chains**
- **Summary**

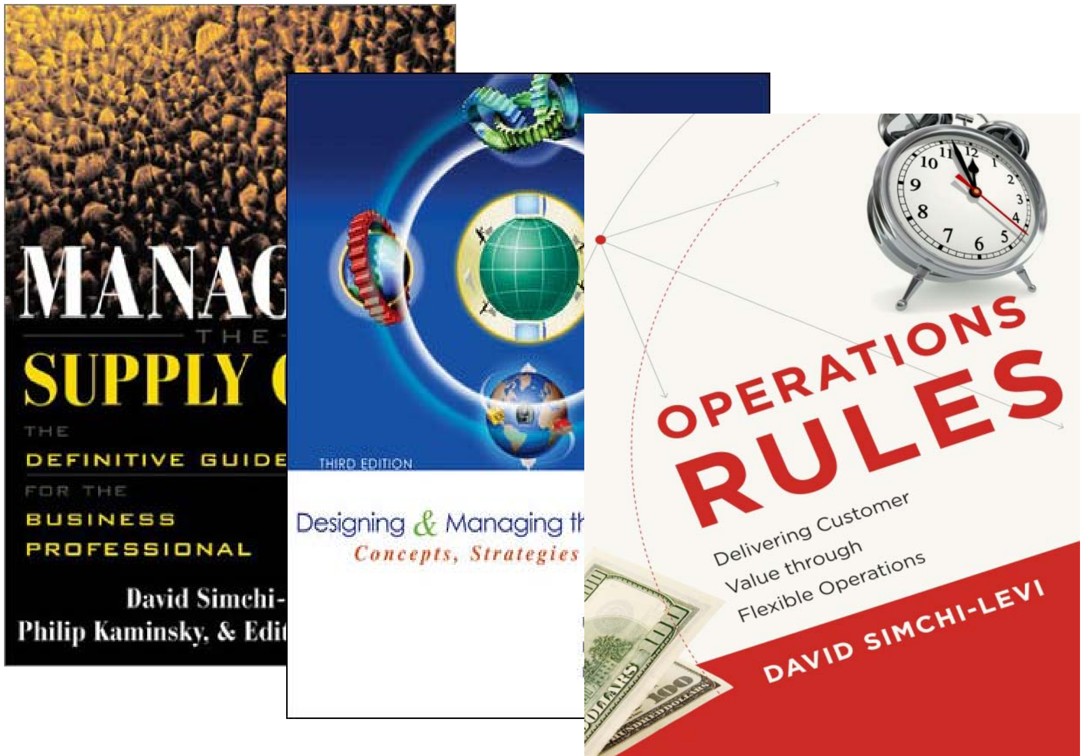


Key Observations

- **The age of Flexibility has arrived**
  - **The Decade of the 80's: Significant disappointment in industry with flexibility (Jaikumar, 1986)**
  - **The Decade of the 90's and early 2000: Higher flexibility in the automotive industry (Van Biesebroeck, 2004)**
  - **Today: More and more companies in diverse industries invest in various types of flexibility (Simchi-Levi, 2010)**

- **More research is needed to help**
  - **Establish design guidelines**
  - **Analyze more realistic business settings (multi-stage, variability up-stream, information sharing)**
  - **Identify the level of flexibility required**

Your Turn!



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