Logistics Systems Design: Supply Chain Models

7. Continuous Point Location
8. Discrete Point Location
9. Supply Chain Models
10. Facilities Design
11. Computer Aided Layout
12. Layout Models

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Supply Chain Models Overview

- Introduction
- Channel Selection Models
- Single Country (Domestic) Models
- Global Models
- Robustness and Flexibility Models

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Current Algorithms Hierarchy: Benchmarking

- Evaluate or benchmark
  - Digital simulation or spreadsheet
- Distribution channel selection
  - Current facilities and capacities
  - Select best channel and inventory levels
  - Spreadsheet or custom programming

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Current Algorithms Hierarchy: Network Optimization

- Network optimization
  - Current facilities and capacities
  - Optimize the product flow
  - Linear programming solver

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Current Algorithms Hierarchy: Location-Allocation

- Moving facilities
  - Current facility status
  - No site-dependent costs
  - Costs proportional to flow
  - Limited location resolution
  - Alternative generating algorithm
- Approximate algorithms
  - Non-linear optimization, specialized heuristics

Current Algorithms Hierarchy: Supply Chain Models

- Supply chain
  - Everything is allowed to change
  - Alternative selecting
  - Site dependent costs
  - Mixed integer programming solver

Supply Chain Modeling Characteristics

- Many different approaches exist
  - Philosophically different
  - Tradeoff between effort and accuracy
- Tradeoff between accuracy and simplicity
  - Data
  - Computational solution effort
  - Solution validation and interpretation
- Validation of computer results a must

Supply Chain Models Overview

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Distribution Channel Selection

- Given supply chain configuration
  - No fixed facility costs
- For each commodity
  - Determine transportation channel
  - Determine cycle and safety inventory

Transportation Mode Selection Computations

$$PC_p = D_p \cdot pc_p$$

$$TC_{mp} = D_p \cdot tc_{mp}$$

$$PIC_{mp} = D_p \cdot v_p \cdot TT_m \cdot HCF = D_p \cdot pic_{mp}$$

$$OCIC_{imp} = \left(TB_{mp}/2\right) \cdot v_p \cdot HCF$$

$$DCIC_{imp} = \left(TB_{mp}/2\right) \cdot \left(v_p + tc_{mp} + pic_{mp}\right) \cdot HCF$$

$$SI_{mp} = k\sqrt{LT_{mp} CV_{mp}^2 + Var_{LT}} \, d_p$$

$$SIC_{mp} = SI_{mp} \cdot \left(v_p + tc_{mp} + pic_{mp}\right) \cdot HCF$$

Transportation Mode Selection Total Cost Computations

$$FSC_{jmp} = \left[TB_{mp} + SI_{mp}\right] \cdot sc_p$$

$$TIC_p = PC_p$$

$$TVC_{mp} = TC_{mp} + PIC_{mp} + OCIC_{imp} + DCIC_{jmp} + SIC_{jmp}$$

$$TFC_{mp} = FSC_{jmp}$$

$$TAC_{mp} = TIC_p + TVC_{mp} + TFC_{mp}$$

Channel Selection Calculations: Ballou Example

Annual Demand	700000			
Annual Holding Cost Rate	0.3			
Unit Production Cost	$30.00			
Unit Annualized Warehouse Cost	$0.00			

	Rail	Piggyback	Truck	Air
Unit Transportation Cost ($)	0.1	0.15	0.2	1.4
Channel Transit Time (days)	21	14	5	2
Transportation Batch Size	70000	35000	35000	17500

	Rail	Piggyback	Truck	Air
Production Cost	$21,000,000	$21,000,000	$21,000,000	$21,000,000
Total Invariant Costs	**$21,000,000**	**$21,000,000**	**$21,000,000**	**$21,000,000**
Transportation Costs	$70,000	$105,000	$140,000	$980,000
In-Transit Inventory	$362,466	$241,644	$86,301	$34,521
Order Fequency per Year	10	20	20	40
Order Cycle Length in Years	0.1	0.05	0.05	0.025
Plant Max Cycle Inventory	70,000	35,000	35,000	17,500
Plant Cycle Inventory Costs	$315,000	$157,500	$157,500	$78,750
Plant Safety Inventory	65,000	29,000	24,500	11,250
Plant Safety Inventory Costs	$585,000	$261,000	$220,500	$101,250
Unit Value at DC	$30.62	$30.50	$30.32	$31.45
DC Max Cycle Inventory	70,000	35,000	35,000	17,500
DC Cycle Inventory Costs	$321,487	$160,100	$159,197	$82,554
DC Safety Inventory	65,000	29,000	24,500	11,250
DC Safety Inventory Costs	$597,047	$265,308	$222,876	$106,141
DC Maximum Inventory	135,000	64,000	59,500	28,750
Total Marginal Costs	**$2,251,000**	**$1,190,552**	**$986,375**	**$1,383,216**
Annualized Warehouse Costs	$0	$0	$0	$0
Total Variant Costs	**$2,251,000**	**$1,190,552**	**$986,375**	**$1,383,216**
Total Cost	**$23,251,000**	**$22,190,552**	**$21,986,375**	**$22,383,216**

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Single Country Supply Chains: Models and Solution Algorithms

- Kuehn and Hamburger
  - Drop ñ add - swap heuristic
- Geoffrion and Graves
  - Bendersí decomposition
- Goetschalckx and Wei
  - Disaggregated MIP formulation with branch and bound with LP relaxation

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Kuehn and Hamburger Characteristics

- Multicommodity (as an extension)
- Zero echelon
- Uncapacitated depots
- Depot handling cost (as an extension)
- Deterministic
- Single period

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Kuehn and Hamburger Characteristics Continued

- Equivalent path or arc formulation (one echelon)
- No customer single sourcing
- ìWeakî formulation

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Kuehn and Hamburger Model

$$\min \quad z = \sum_{j=1}^{N} \left(f_j y_j + \sum_{i=1}^{M} c_{ij} x_{ij} \right)$$

$$s.t. \quad \sum_{j=1}^{N} x_{ij} = 1 \qquad \forall i$$

$$\sum_{i=1}^{M} x_{ij} - M y_j \le 0 \qquad \forall j$$

$$y_j \in \{0,1\}, x_{ij} \ge 0$$

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Kuehn and Hamburger Formulation Characteristics

- Fixed facility cost (f) and variable transportation cost (c)
- Flow (x) modeled as fraction of total customer demand
- Uncapacitated
- Two type of constraints
  - Demand satisfaction
  - Linkage or consistency

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Site Relative Cost

- u_i = current best cost for servicing customer i
- ρ_j = relative cost for opening warehouse j

$$\rho_j(\mathbf{U}) = f_j + \sum_{i=1}^{M} \min\{0, c_{ij} - u_i\}$$

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Drop-Add-Swap Heuristic

- Drop
  - Start with all facilities open
  - Close the one with the largest relative site cost
  - Until no further decrease in costs
- Add
  - Start with all facilities closed
  - Open the one with the most negative relative site cost
  - Until no further decrease in costs

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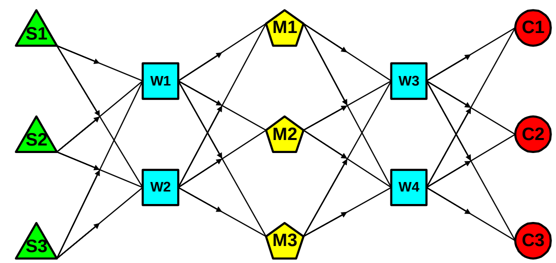
Drop-Add-Swap Heuristic

- Swap
  - Start with drop
  - Swap (open and close) the two facilities with the most extreme relative site cost
  - Until not further cost reduction

Kuehn and Hamburger, (1963), ì A Heuristic Program for Locating Warehouses,î Management Science, *Vol. 9, pp. 643-666.*

Supply Chain Example: Schematic



Supply Chain Example: Transportation Data

Microsoft Excel - Supply Chain Design Example.xls

Cost Data

Transportation Step 1 (Supplier-Warehouse)				Transportation Step 3 (Manufacturing-Warehousing)		
P1	W1	W2		P1	W3	W4
S1	1	2		M1	2	1
S2	2	3		M2	3	2
S3	1	1		M3	2	3
P2	W1	W2		P2	W3	W4
S1	3	2		M1	1	2
S2	4	2		M2	2	1
S3	2	1		M3	3	4

Transportation Step 2 (Warehouse-Manufacturing)				Transportation Step 4 (Warehouse-Customer)			
P1	M1	M2	M3	P1	C1	C2	C3
W1	2	1	1	W3	2	3	2
W2	3	2	1	W4	1	2	3
P2	M1	M2	M3	P2	C1	C2	C3
W1	1	3	2	W3	1	2	3
W2	1	2	3	W4	2	1	4

Data / Model / Solution

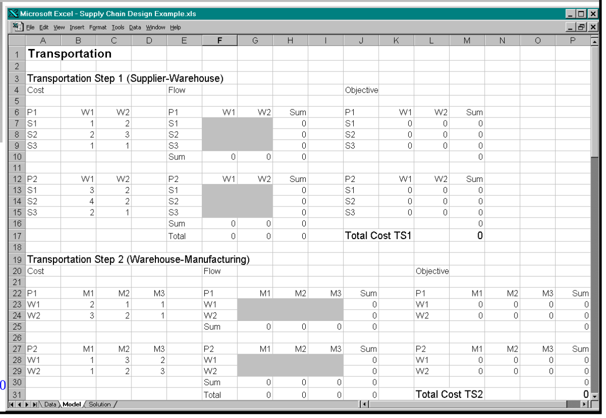
Supply Chain Example: Capacity and Facility Data

Microsoft Excel - Supply Chain Design Example.xls

Capacities		**Customer Demands**			
Supplier Capacity			C1	C2	C3
		P1	100	75	25
S1	300	P2	100	100	40
S2	400				
S3	200				
Warehousing Capacity (Throughput)		**Facility Costs**			
W1	300	S1	100		
W2	350	S2	200		
W3	300	S3	300		
W4	350	W1	50		
		W2	80		
Manufacturing		M1	250		
		M2	200		
M1	500	M3	50		
M2	400	W3	50		
M3	300	W4	80		

Data / Model / Solution

Supply Chain Example: Model Purchasing Flows



Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Transportation**															
2																
3	Transportation Step 1 (Supplier-Warehouse)															
4	Cost				Flow					Objective						
5																
6	P1	W1	W2		P1	W1	W2	Sum		P1	W1	W2	Sum			
7	S1	1	2		S1			0		S1	0	0	0			
8	S2	2	3		S2			0		S2	0	0	0			
9	S3	1	1		S3			0		S3	0	0	0			
10					Sum	0	0	0					0			
11																
12	P2	W1	W2		P2	W1	W2	Sum		P2	W1	W2	Sum			
13	S1	3	2		S1			0		S1	0	0	0			
14	S2	4	2		S2			0		S2	0	0	0			
15	S3	2	1		S3			0		S3	0	0	0			
16					Sum	0	0	0					0			
17					Total	0	0	0		Total Cost TS1			0			
18																
19	Transportation Step 2 (Warehouse-Manufacturing)															
20	Cost					Flow						Objective				
21																
22	P1	M1	M2	M3		P1	M1	M2	M3	Sum		P1	M1	M2	M3	Sum
23	W1	2	1	1		W1				0		W1	0	0	0	0
24	W2	3	2	1		W2				0		W2	0	0	0	0
25						Sum	0	0	0	0						0
26																
27	P2	M1	M2	M3		P2	M1	M2	M3	Sum		P2	M1	M2	M3	Sum
28	W1	1	3	2		W1				0		W1	0	0	0	0
29	W2	1	2	3		W2				0		W2	0	0	0	0
30						Sum	0	0	0	0						0
31						Total	0	0	0	0		Total Cost TS2				0

Data / Model / Solution

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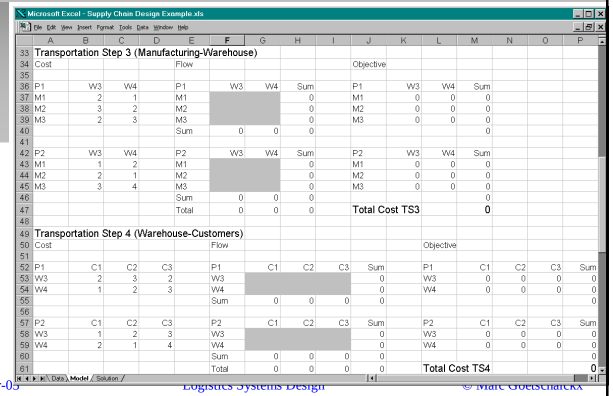
Supply Chain Example: Model Distribution Flows



Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
33	Transportation Step 3 (Manufacturing-Warehouse)															
34	Cost				Flow					Objective						
35																
36	P1	W3	W4		P1	W3	W4	Sum		P1	W3	W4	Sum			
37	M1	2	1		M1			0		M1	0	0	0			
38	M2	3	2		M2			0		M2	0	0	0			
39	M3	2	3		M3			0		M3	0	0	0			
40					Sum	0	0	0					0			
41																
42	P2	W3	W4		P2	W3	W4	Sum		P2	W3	W4	Sum			
43	M1	1	2		M1			0		M1	0	0	0			
44	M2	2	1		M2			0		M2	0	0	0			
45	M3	3	4		M3			0		M3	0	0	0			
46					Sum	0	0	0					0			
47					Total	0	0	0		Total Cost TS3			0			
48																
49	Transportation Step 4 (Warehouse-Customers)															
50	Cost					Flow						Objective				
51																
52	P1	C1	C2	C3		P1	C1	C2	C3	Sum		P1	C1	C2	C3	Sum
53	W3	2	3	2		W3				0		W3	0	0	0	0
54	W4	1	2	3		W4				0		W4	0	0	0	0
55						Sum	0	0	0	0						0
56																
57	P2	C1	C2	C3		P2	C1	C2	C3	Sum		P2	C1	C2	C3	Sum
58	W3	1	2	3		W3				0		W3	0	0	0	0
59	W4	2	1	4		W4				0		W4	0	0	0	0
60						Sum	0	0	0	0						0
61						Total	0	0	0	0		Total Cost TS4				0

Data / Model / Solution

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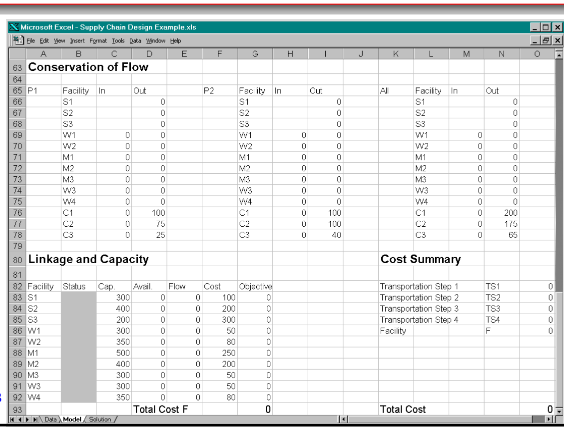
Supply Chain Example: Model Capacity and Facility Costs



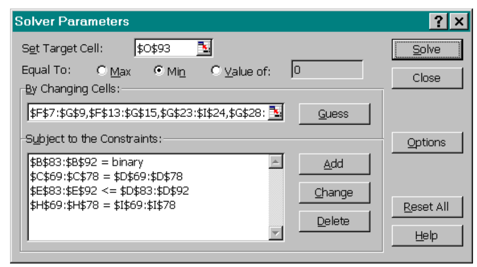
Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
63	**Conservation of Flow**														
64															
65	P1	Facility	In	Out		P2	Facility	In	Out		All	Facility	In	Out	
66		S1		0			S1		0			S1		0	
67		S2		0			S2		0			S2		0	
68		S3		0			S3		0			S3		0	
69		W1	0	0			W1	0	0			W1	0	0	
70		W2	0	0			W2	0	0			W2	0	0	
71		M1	0	0			M1	0	0			M1	0	0	
72		M2	0	0			M2	0	0			M2	0	0	
73		M3	0	0			M3	0	0			M3	0	0	
74		W3	0	0			W3	0	0			W3	0	0	
75		W4	0	0			W4	0	0			W4	0	0	
76		C1	0	100			C1	0	100			C1	0	200	
77		C2	0	75			C2	0	100			C2	0	175	
78		C3	0	25			C3	0	40			C3	0	65	
79															
80	**Linkage and Capacity**										**Cost Summary**				
81															
82	Facility	Status	Cap.	Avail.	Flow	Cost	Objective				Transportation Step 1			TS1	0
83	S1		300	0	0	100	0				Transportation Step 2			TS2	0
84	S2		400	0	0	200	0				Transportation Step 3			TS3	0
85	S3		200	0	0	300	0				Transportation Step 4			TS4	0
86	W1		300	0	0	50	0				Facility			F	0
87	W2		350	0	0	80	0								
88	M1		500	0	0	250	0								
89	M2		400	0	0	200	0								
90	M3		300	0	0	50	0								
91	W3		300	0	0	50	0								
92	W4		350	0	0	80	0								
93				Total Cost F			0				Total Cost				0

Data / Model / Solution

18-Mar-03

Supply Chain Example: Model Excel Solver



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Supply Chain Example: Solution Flows (Purchasing)

Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Transportation**															
2																
3	Transportation Step 1 (Supplier-Warehouse)															
4	Cost				Flow					Objective						
5																
6	P1	W1	W2		P1	W1	W2	Sum		P1	W1	W2	Sum			
7	S1	1	2		S1	200	0	200		S1	200	0	200			
8	S2	2	3		S2	0	0	0		S2	0	0	0			
9	S3	1	1		S3	0	0	0		S3	0	0	0			
10					Sum	200	0	200					200			
11																
12	P2	W1	W2		P2	W1	W2	Sum		P2	W1	W2	Sum			
13	S1	3	2		S1	0	40	40		S1	0	80	80			
14	S2	4	2		S2	0	0	0		S2	0	0	0			
15	S3	2	1		S3	0	200	200		S3	0	200	200			
16					Sum	0	240	240					280			
17					Total	200	240	440		**Total Cost TS1**			**480**			
18																
19	Transportation Step 2 (Warehouse-Manufacturing)															
20	Cost					Flow						Objective				
21																
22	P1	M1	M2	M3		P1	M1	M2	M3	Sum		P1	M1	M2	M3	Sum
23	W1	2	1	1		W1	200	0	0	200		W1	400	0	0	400
24	W2	3	2	1		W2	0	0	0	0		W2	0	0	0	0
25						Sum	200	0	0	200						400
26																
27	P2	M1	M2	M3		P2	M1	M2	M3	Sum		P2	M1	M2	M3	Sum
28	W1	1	3	2		W1	0	0	0	0		W1	0	0	0	0
29	W2	1	2	3		W2	240	0	0	240		W2	240	0	0	240
30						Sum	240	0	0	240						240
31						Total	440	0	0	440		**Total Cost TS2**				**640**

Data / Model / Solution

Supply Chain Example: Solution Flows (Distribution)

Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
33	Transportation Step 3 (Manufacturing-Warehouse)															
34	Cost				Flow					Objective						
35																
36	P1	W3	W4		P1	W3	W4	Sum		P1	W3	W4	Sum			
37	M1	2	1		M1	25	175	200		M1	50	175	225			
38	M2	3	2		M2	0	0	0		M2	0	0	0			
39	M3	2	3		M3	0	0	0		M3	0	0	0			
40					Sum	25	175	200					225			
41																
42	P2	W3	W4		P2	W3	W4	Sum		P2	W3	W4	Sum			
43	M1	1	2		M1	140	100	240		M1	140	200	340			
44	M2	2	1		M2	0	0	0		M2	0	0	0			
45	M3	3	4		M3	0	0	0		M3	0	0	0			
46					Sum	140	100	240					340			
47					Total	165	275	440		**Total Cost TS3**			**565**			
48																
49	Transportation Step 4 (Warehouse-Customers)															
50	Cost					Flow						Objective				
51																
52	P1	C1	C2	C3		P1	C1	C2	C3	Sum		P1	C1	C2	C3	Sum
53	W3	2	3	2		W3	0	0	25	25		W3	0	0	50	50
54	W4	1	2	3		W4	100	75	0	175		W4	100	150	0	250
55						Sum	100	75	25	200						300
56																
57	P2	C1	C2	C3		P2	C1	C2	C3	Sum		P2	C1	C2	C3	Sum
58	W3	1	2	3		W3	100	0	40	140		W3	100	0	120	220
59	W4	2	1	4		W4	0	100	0	100		W4	0	100	0	100
60						Sum	100	100	40	240						320
61						Total	200	175	65	440		**Total Cost TS4**				**620**

Data / Model / Solution

Supply Chain Example: Solution Costs

Microsoft Excel - Supply Chain Design Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
63	**Conservation of Flow**														
64															
65	P1	Facility	In	Out		P2	Facility	In	Out		All	Facility	In	Out	
66		S1		200			S1		40			S1		240	
67		S2		0			S2		0			S2		0	
68		S3		0			S3		200			S3		200	
69		W1	200	200			W1	0	0			W1	200	200	
70		W2	0	0			W2	240	240			W2	240	240	
71		M1	200	200			M1	240	240			M1	440	440	
72		M2	0	0			M2	0	0			M2	0	0	
73		M3	0	0			M3	0	0			M3	0	0	
74		W3	25	25			W3	140	140			W3	165	165	
75		W4	175	175			W4	100	100			W4	275	275	
76		C1	100	100			C1	100	100			C1	200	200	
77		C2	75	75			C2	100	100			C2	175	175	
78		C3	25	25			C3	40	40			C3	65	65	
79															
80	**Linkage and Capacity**										**Cost Summary**				
81															
82	Facility	Status	Cap.	Avail.	Flow	Cost	Objective				Transportation Step 1			TS1	480
83	S1	1	300	300	240	100	100				Transportation Step 2			TS2	640
84	S2	0	400	0	0	200	0				Transportation Step 3			TS3	565
85	S3	1	200	200	200	300	300				Transportation Step 4			TS4	620
86	W1	1	300	300	200	50	50				Facility			F	910
87	W2	1	350	350	240	80	80								
88	M1	1	500	500	440	250	250								
89	M2	0	400	0	0	200	0								
90	M3	0	300	0	0	50	0								
91	W3	1	300	300	165	50	50								
92	W4	1	350	350	275	80	80								
93				Total Cost F			910				Total Cost				3215

Data / Model / Solution

Arc Based Formulations

- From an origin facility to a destination facility
- Advantages
  - Fewer variables
  - Simpler model
  - Scales better to multiple echelons
- Disadvantage
  - Numerous conservation of flow constraints

Arc Based Conservation of Flow Constraints

- 10 manufacturing plants
- 20 distribution centers
- 200 customers
- 40 products
- 20*40=800 flow conservation constraints

Path Based Formulations

- Flow from original supplier to final customer
- Advantages
  - Allows path related constraints (time to market, system safety inventory)
- Disadvantages
  - Number of variables explodes with echelons

Path Based Formulation Number of Variables

- 10 manufacturing plants
- 20 distribution centers
- 200 customers
- 40 products
- 10*20*200*40 =1.6 million variables

Geoffrion & Graves Characteristics

- Multicommodity
- Single echelon
- Capacitated depots (lower and upper bound)
- Depot handling cost
- Deterministic
- Single Period

Geoffrion & Graves Characteristics Continued

- Path formulation
- Customer single sourcing
- ìWeakî formulation
- Additional linear constraints in z and y

Geoffrion and Graves Model

$$\min \sum_{ijkp} c_{ijkp} x_{ijkp} + \sum_{j} \left(f_j z_j + h_j \sum_{kp} r_{kp} y_{jk} \right)$$

$$s.t. \quad \sum_{jk} x_{ijkp} \le s_{ip} \qquad \forall ip$$

$$\sum_{i} x_{ijkp} = r_{kp} y_{jk} \qquad \forall jk$$

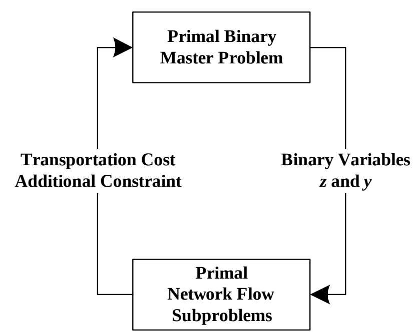
$$\sum_{j} y_{jk} = 1 \qquad \forall k$$

$$TL_j z_j \le \sum_{pk} r_{kp} y_{jk} \le TU_j z_j \qquad \forall j$$

Benders Primal Decomposition

- Fix binary variables z and y
  - ï Solve independent commodity network flow problems
  - ï Determine total transportation cost
- Add total transportation cost as a cut to binary master problem
- Solve binary master problem
- Iterate

Benders Decomposition Flow Chart



Primal Network Subproblem

$$\begin{aligned} \min \quad & \sum_{ijkp} c_{ijkp} x_{ijkp} \\ s.t. \quad & \sum_{jk} x_{ijkp} \le s_{ip} & [v_{ip}] \\ & \sum_{i} x_{ijkp} = r_{kp} y_{jk} & [u_{jkp}] \\ & x_{ijkp} \ge 0 \end{aligned}$$

Note that *y* are parameters, not variables

Dual Network Subproblem

$$\begin{aligned} \max \quad & y_0 = \sum_{ip} -v_{ip} s_{ip} + \sum_{jkp} u_{jkp} r_{kp} y_{jk} \\ s.t. \quad & u_{jkp} - v_{ip} \le c_{ijkp} \qquad \forall ijkp \\ & v_{ip} \ge 0, \; u_{jkp} \; unrestricted \end{aligned}$$

Note that *y* are parameters, not variables

Extreme Point Formulation and Constraint

$$\max_{\left[v_{ip}^e, u_{jkp}^e\right] \in E} y_0 = \sum_{ip} -v_{ip}^e s_{ip} + \sum_{jkp} u_{jkp}^e r_{kp} y_{jk}$$

$$y_0 \ge \sum_{ip} -v_{ip}^e s_{ip} + \sum_{jkp} u_{jkp}^e r_{kp} y_{jk} \qquad \forall e$$

Primal Binary Master Problem

$$\begin{aligned} \min \quad & \sum_{j} \left(f_j z_j + h_j \sum_{kp} r_{kp} y_{jk} \right) + y_0 \\ s.t. \quad & \sum_{j} y_{jk} = 1 & \forall k \\ & TL_j z_j \le \sum_{pk} r_{kp} y_{jk} \le TU_j z_j & \forall j \\ & y_0 \ge \sum_{ip} -v_{ip}^e s_{ip} + \sum_{jkp} u_{jkp}^e r_{kp} y_{jk} & e = 1..E \\ & z, \; y \in \{0,1\}, \; y_0 \ge 0 \end{aligned}$$

Benders Decomposition Method References

- Geoffrion and Graves, (1974). "Multicommodity Distribution System Design by Benders Decomposition." Management Science, Vol. 20, No. 5, pp. 822-844.
- Lasdon, (1970). Optimization Theory for Large Systems. MacMillan Publishing Co., New York, New York.
- Van Roy, (1986). ìA Cross Decomposition Algorithm for Capacitated Facility Location.î Operations Research, Vol. 34, No. 1, pp. 145-163.

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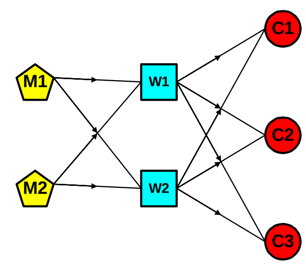
Supply Chain Ballou Example: Schematic



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Supply Chain Ballou Example: Transportation Data

Microsoft Excel - Supply Chain Design Ballou Example.xls

	A	B	C	D	E	F	G	H	I	J
1	**Cost Data**									
2										
3	Transportation Step 1 (Plant-Warehouse)					Transportation Step 2 (Warehouse-Customer				
4										
5		Cost	Destination				Cost	Destination		
6	Product	Origin	W1	W2		Product	Origin	C1	C2	C3
7	P1	P1	0	5		P1	W1	4	3	5
8		P2	4	2			W2	2	1	2
9										
10	P2	P1	0	5		P2	W1	3	2	4
11		P2	4	2			W2	3	2	3
12										
13	**Production**				**Handling**				**Facility Costs**	
14										
15	Product	Plant	Cost		Product	Warehous	Cost		Facility	Cost
16	P1	P1	4		P1	W1	2		W1	100000
17		P2	4			W2	1		W2	500000
18										
19	P2	P1	3		P2	W1	2			
20		P2	2			W2	1			

Data / Model / Solution / Fleet Sizing / Path Model / Path Solution

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Supply Chain Ballou Example: Capacity Data

Microsoft Excel - Supply Chain Design Ballou Example.xls

	A	B	C	D	E	F	G	H
22	**Capacities**							
23								
24	Warehouse Capacity (Throughput)					Production		
25								
26	Facility	Capacity				Product	Facility	Capacity
27	W1	110000				P1	P1	60000
28	W2						P2	
29						P2	P1	50000
30							P2	
31	**Customer Demands**							
32								
33	Product	C1	C2	C3				
34	P1	50000	100000	50000				
35	P2	20000	30000	60000				

Data / Model / Solution / Fleet Sizing / Path Model / Path Solution

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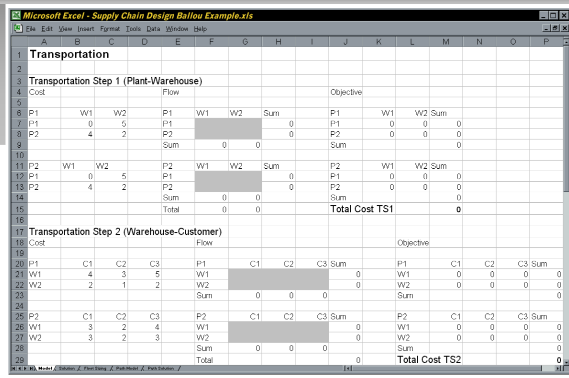
Supply Chain Ballou Example: Arc Transportation Model



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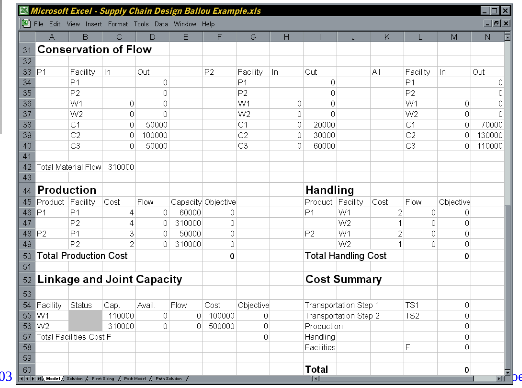
Supply Chain Ballou Example: Arc Capacity Model



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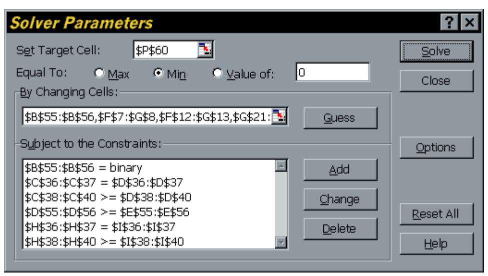
Supply Chain Ballou Example: Arc Solver



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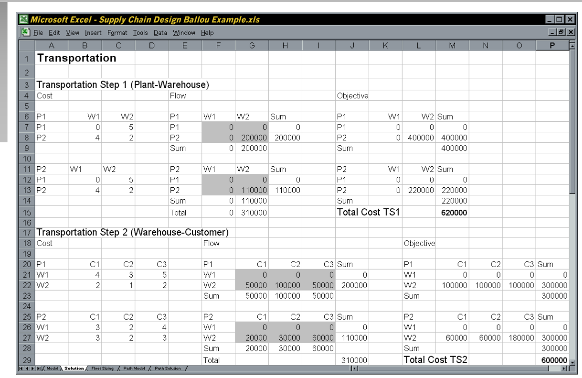
Supply Chain Ballou Example: Arc Transportation Solution



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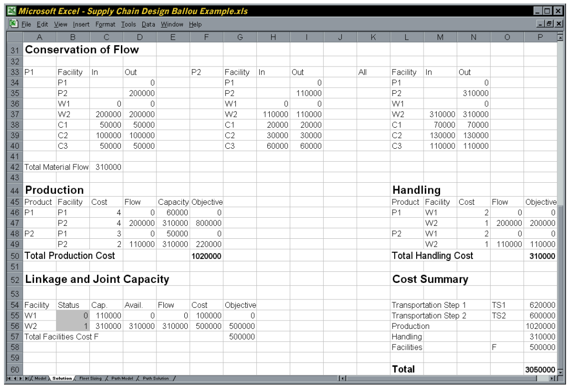
Supply Chain Ballou Example: Arc Capacity Solution



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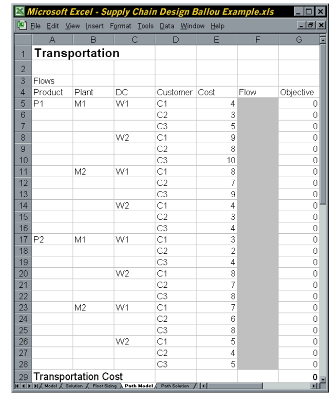
Supply Chain Ballou Example: Path Transportation Model



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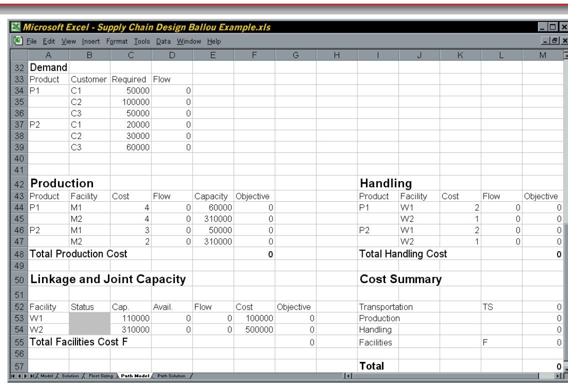
Supply Chain Ballou Example: Path Capacity Model



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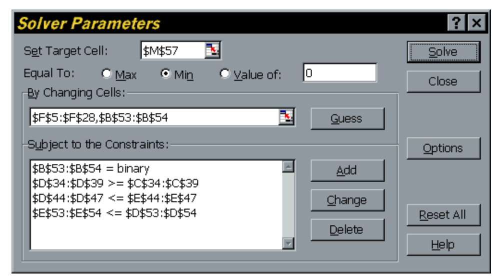
Supply Chain Ballou Example: Path Solver



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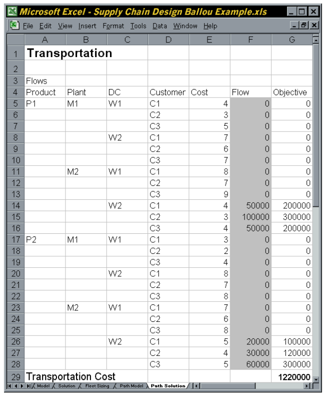
Supply Chain Ballou Example: Path Transportation Solution



Microsoft Excel - Supply Chain Design Ballou Example.xls

	A	B	C	D	E	F	G
1	**Transportation**						
2							
3	Flows						
4	Product	Plant	DC	Customer	Cost	Flow	Objective
5	P1	M1	W1	C1	4	0	0
6				C2	3	0	0
7				C3	5	0	0
8			W2	C1	7	0	0
9				C2	6	0	0
10				C3	7	0	0
11		M2	W1	C1	8	0	0
12				C2	7	0	0
13				C3	9	0	0
14			W2	C1	4	50000	200000
15				C2	3	100000	300000
16				C3	4	50000	200000
17	P2	M1	W1	C1	3	0	0
18				C2	2	0	0
19				C3	4	0	0
20			W2	C1	8	0	0
21				C2	7	0	0
22				C3	8	0	0
23		M2	W1	C1	7	0	0
24				C2	6	0	0
25				C3	8	0	0
26			W2	C1	5	20000	100000
27				C2	4	30000	120000
28				C3	5	60000	300000
29	Transportation Cost						**1220000**

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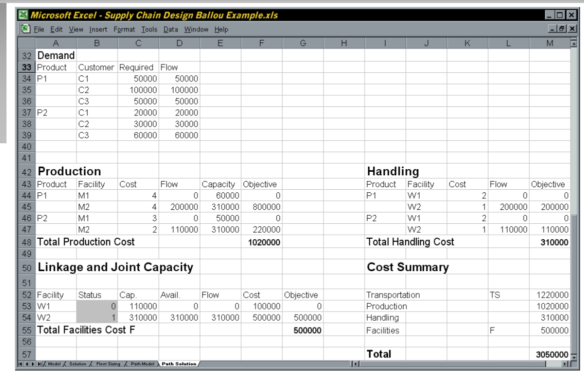
Supply Chain Ballou Example: Path Capacity Solution



Microsoft Excel - Supply Chain Design Ballou Example.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M
32	**Demand**												
33	Product	Customer	Required	Flow									
34	P1	C1	50000	50000									
35		C2	100000	100000									
36		C3	50000	50000									
37	P2	C1	20000	20000									
38		C2	30000	30000									
39		C3	60000	60000									
40													
41													
42	**Production**								**Handling**				
43	Product	Facility	Cost	Flow	Capacity	Objective			Product	Facility	Cost	Flow	Objective
44	P1	M1	4	0	60000	0			P1	W1	2	0	0
45		M2	4	200000	310000	800000				W2	1	200000	200000
46	P2	M1	3	0	50000	0			P2	W1	2	0	0
47		M2	2	110000	310000	220000				W2	1	110000	110000
48	Total Production Cost					**1020000**			Total Handling Cost				**310000**
49													
50	**Linkage and Joint Capacity**								**Cost Summary**				
51													
52	Facility	Status	Cap.	Avail.	Flow	Cost	Objective		Transportation			TS	1220000
53	W1	0	110000	0	0	100000	0		Production				1020000
54	W2	1	310000	310000	310000	500000	500000		Handling				310000
55	Total Facilities Cost F						**500000**		Facilities			F	500000
56													
57									**Total**				**3050000**

Model / Solution / Fleet Sizing / Path Model / Path Solution

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Logistics Modeling Trends

- Computer software trends
  - More capable MIP solvers
  - Modeling languages
  - ERP systems (with some optimization)
- Acceptance of integrated supply chain view
  - More comprehensive models (cradle to grave)
  - More realistic models (inventory)

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Logistics Modeling Trends: Conclusions

- Models growing in complexity and realism
- Models developed by supply chain owners
- Solution techniques become more generic and ìshrink wrappedî

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SMILE Characteristics

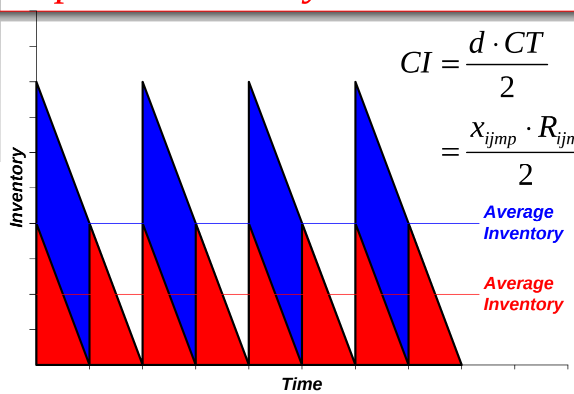
- Multicommodity
- Multi-echelon
- Capacitated facilities
- Capacitated channels
- All costs
- Deterministic
- Single period
- Domestic (single country)

SMILE Characteristics (2)

- Arc formulation
- Safety inventory proportional to demand (user determined)
- Production cost and capacities
- Weight and volume capacities
- Depot and product single sourcing
- Smart (tight) formulations
- CPLEX MIP module

Cycle Inventory versus Replenishment Cycle Time

$$CI = \frac{d \cdot CT}{2} = \frac{x_{ijmp} \cdot R_{ijm}}{2}$$



Number of Carriers

- Weight capacity

$$\sum_{p \in P} \mathrm{Wt}_p x_{ijmp} \leq \mathrm{CarrierWtCap}_{ijm} w_{ijm}$$

- Volume capacity

$$\sum_{p \in P} \mathrm{Vol}_p x_{ijmp} \leq \mathrm{CarrierVolCap}_{ijm} w_{ijm}$$

w_{ijm} = # carriers per time period

x_{ijmp}=flow of product p per time period

Number of Carrier Constraints

- 25 distribution centers
- 400 customers
- 3 products
- 25*400*3*2 = 60,000 constraints

Transportation Costs

- Carrier cost
- Material flow cost

$$\sum_{i \in B \cup D} \sum_{j \in C \cup D} \sum_{m \in M(i,j)} \left[\begin{array}{l} \text{CarrierCost}_{ijm} w_{ijm} + \\ \sum_{p \in P} \text{TranUnitCost}_{ijmp} x_{ijmp} \end{array} \right]$$

Safety Inventory Versus Lead Time

$$SI = k \cdot \sqrt{LT \cdot Var_d + d^2 \cdot Var_{LT}}$$

$$CV_d = \frac{\sqrt{Var_d}}{d}$$

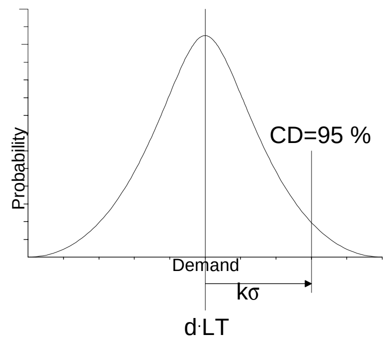
$$Var_d = \left(CV_d \cdot d \right)^2$$

$$SI = k \cdot \sqrt{LT \cdot CV_d^2 + Var_{LT}} \cdot d$$

Safety Stock Inventory Factor

- Customer service measured by probability of a stock-out
- Safety inventory commonly equals time length multiplied by demand (linear safety inventory policies)

Demand During Lead Time and Stock-out Probability



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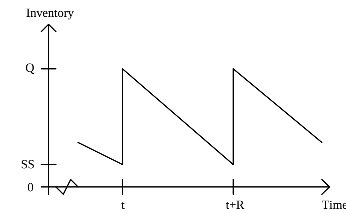
Warehouse Inventory Cost



$$\sum_{i\in B\cup D}\sum_{j\in D}\sum_{m\in M(i,j)}\sum_{p\in P} r\,\text{Value}_p\left(\text{SSFactor}_{jp}+\frac{R_{ijm}}{2}\right)x_{ijmp}$$

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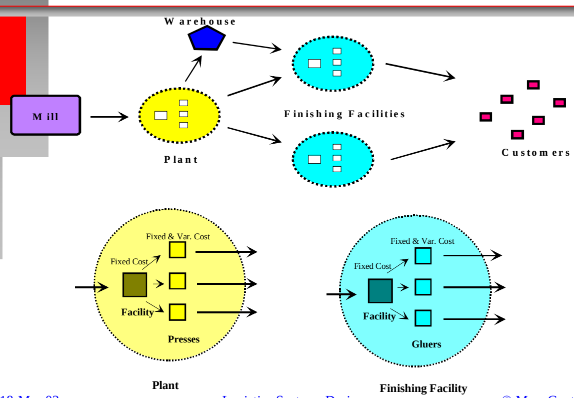
Machine Resources Schematic



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SMILE Case Studies

- *Hospital supply company*
- *State of New Jersey recycling*
- *Electronics manufacturing*
- *HAC wholesaler*
- *Paper packaging supplier*

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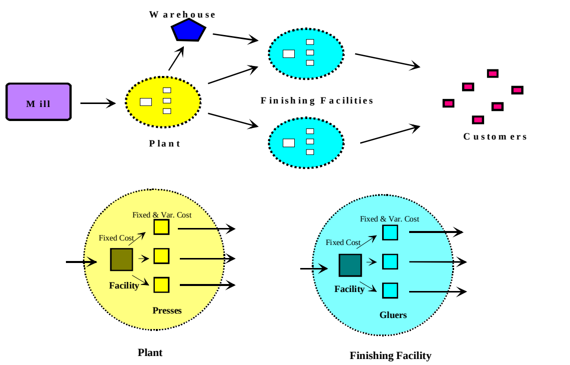
Cardboard Manufacturer Supply Chain Schematic



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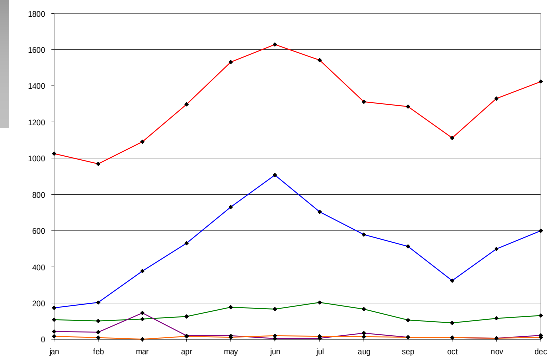
Seasonal Demand Pattern (Soft Drinks)



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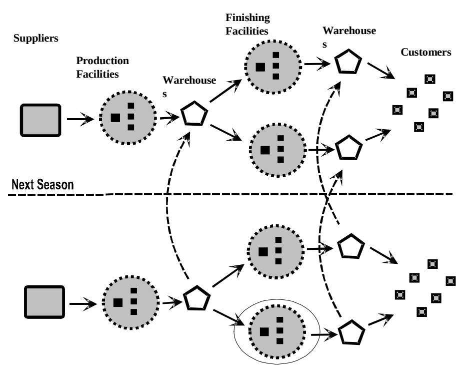
Seasonal Material Flow Schematic



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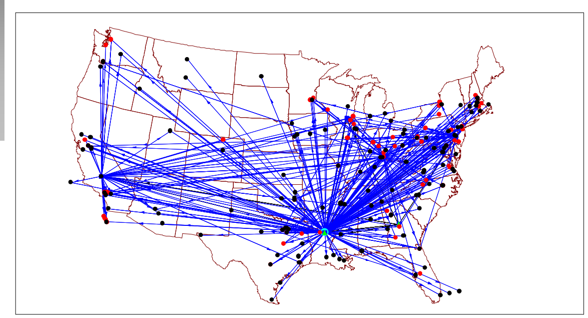
Initial Supply Chain



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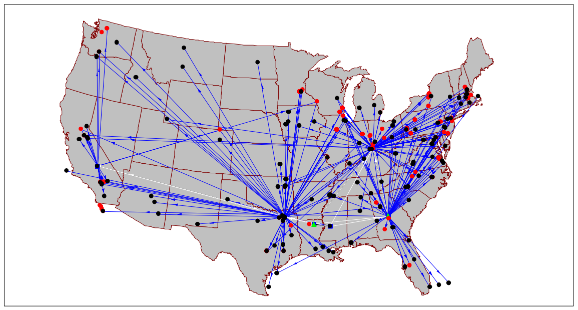
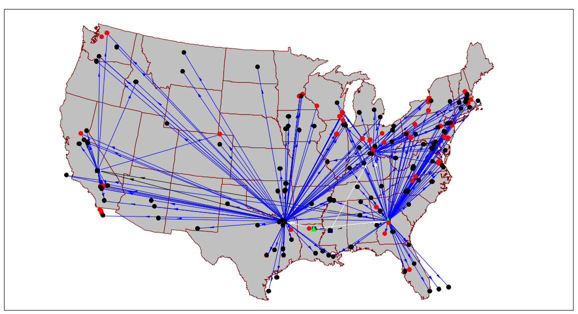
Single Season Improved Supply Chain



Cardboard Packaging Manufacturer

- 3 seasons, 2 stage manufacturing
- 12 products, 714 customers
- 87 production lines
- 3738 transportation channels
- 48888 variables (102 integer)
- primal decomposition reduced run times from 2 days to 865 seconds
- savings $8.3 million

Seasonal Improved Supply Chain



Supply Chain Models Overview

- Introduction
- Channel Selection Models
- Single Country (Domestic) Models
- **Global Models**
- Robustness and Flexibility Models

Global Logistics Systems Models

- Domestic plus exchange rates, duties, taxes
- Objective is worldwide after-tax profit maximization
- Decisions are material flows, transportation cost allocations, and transfer prices

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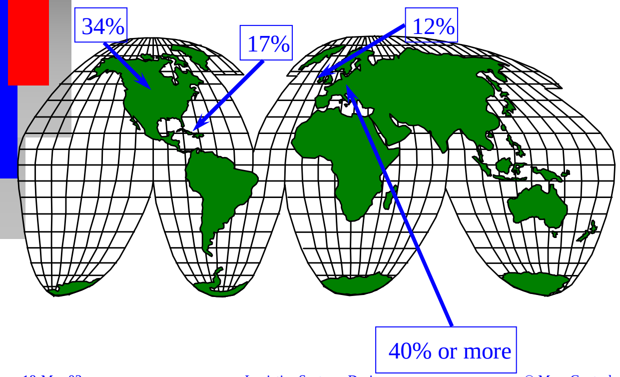
Tax Rates and Profit Realization



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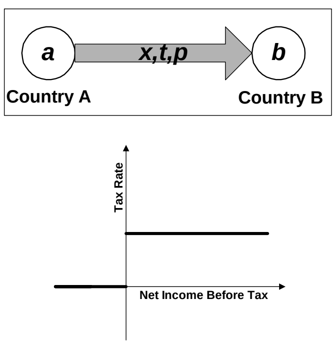
Global Transactions and Tax Rates



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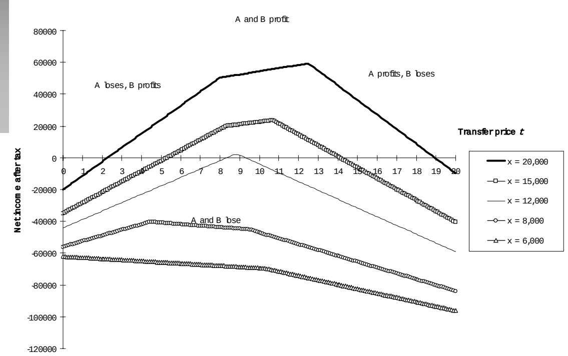
Impact of Transfer Prices on After Tax Profits



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Before and After Tax Profit Objective and Constraint

$$\max : (1 - taxrate_k) ibtwf_k^+ - ibtwf_k^-$$

subject to :

$$\sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{1}{E_l}\right) MPRICE_{lp} w_{klmp} - \sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{1}{E_k}\right) \left[HANDC_{kp} + TRCWM_{klm} W_p\right] w_{klmp}$$

$$- \sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{VP_{kp} H}{E_k}\right) \left[TTWM_{klm} + (CSF)\ SHIPFREQ_{klm} + SSFW_{kp} \sqrt{TTWM_{klm}}\right] w_{klmp}$$

$$- \sum_{j \in M} \sum_{m \in T(j,k)} \sum_{p \in P(j)} \left(\frac{1}{E_j}\right) \left[tppldc_{jp} \left(1 + DUTY_{jkp}\right) + \left(1 - propw_{jkm}\right)\ TRCPW_{jkm} W_p\right] x_{jkmp}$$

$$- \left(\frac{1}{E_k}\right) FIXDC_k = ibtwf_k^+ - ibtwf_k^- \qquad k \in W^f$$

Computational Test Case

- 50 raw material suppliers
- 8 plants, 10 distribution centers
- 80 customers
- 35 components, 12 finished products
- 3.1 modes per channel
- 10100 variables, 2900 constraints

Profit Increases for Optimal Transfer Prices

	Transfer Price Heuristics			
Instance	Middle Point	Tax Rate	Lower Bound	Upper Bound
1	2.4	0.2	0.8	4.1
2	23.2	12.1	17.1	29.2
3	22.6	30.2	39.9	16.2
4	45.6	65.0	95.2	32.1

Supply Chain Models Overview

- Introduction
- Channel Selection Models
- Single Country (Domestic) Models
- Global Models
- **Robustness and Flexibility Models**

Design of Robust and Flexible Supply Chains

- Change in the mission and data is inevitable, but only techniques are sensitivity and scenario analysis
- No scientific analysis or design methodology for large SC problems
- Needed measures of
  - Flexibility (configuration feasibility)
  - Robustness (quality of objective)

Research Review

- Extensive literature on deterministic or scenario-based supply chain design
- Flexibility definitions in manufacturing research (FMS) appear not applicable
- Stochastic optimization for small problems
- Some stochastic optimization for exchange rates in global systems

Robustness and Flexibility

- Relative robustness, Kouvelis (1997)

$$\max_{s \in S} \left\{ \frac{z_s(x_R) - z_s^*(x_s^*)}{z_s^*(x_s^*)} \right\}$$

- Flexibility, Beamon (1998)
  - Unused capacity in a configuration

Hierarchical Stochastic Design Algorithm

- Select a limited number of feasible supply chain configurations
- For each configuration
  - Sample parameters from distributions
  - Solve linear network flow problems
  - Compute expected value and variance
- Select ìbestî configuration
  - Weighted objective or efficiency frontier

Hierarchical Two-stage Formulation

$$\begin{aligned} Min \quad & cx + dy \\ s.t. \quad & Ex + Fy \le h \\ & Hx \le g \\ & x \in \{0,1\}, y \ge 0 \end{aligned}$$

$$\begin{aligned} Min \quad & cx + E\left[Q(x,\xi)\right] \\ s.t. \quad & Hx \le g \\ & x \in \{0,1\} \end{aligned} \qquad Q(x,\xi) = \begin{aligned} Min \quad & dy \\ s.t. \quad & Fy \le h - Ex \\ & y \ge 0 \end{aligned}$$

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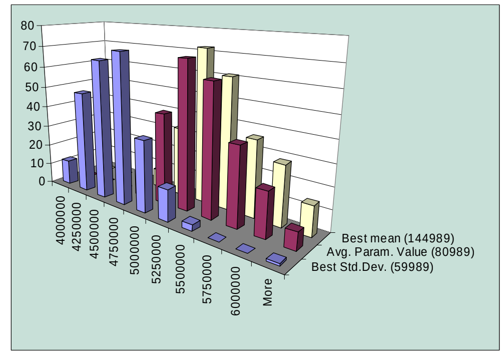
Second Stage Profit Distributions (Medium Example)



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Multicriteria Formulation

$$\begin{aligned} Min \quad & cx + E\left[Q(x,\xi)\right] + \alpha \cdot SD\left[Q(x,\xi)\right] \\ s.t. \quad & Hx \le g \\ & x \in \{0,1\} \end{aligned}$$

But standard Deviation (SD) is not convex

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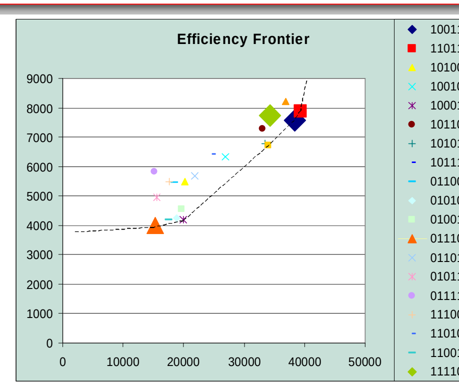
Multi-objective Criteria and Efficiency Frontier (Medium)



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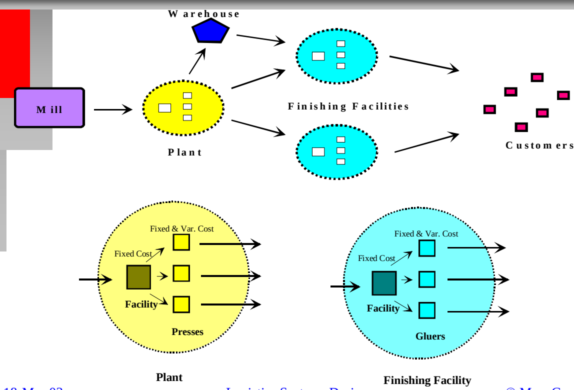
Approximations

$$E\left[Q(x,\xi)\right] \approx \frac{1}{N}\sum_{i=1}^{N} Q\left(x,\xi^{i}\right)$$

$$SD\left[Q(x,\xi)\right] = \sqrt{Var\left[Q(x,\xi)\right]}$$

$$Var\left[Q(x,\xi)\right] \approx \frac{1}{N}\sum_{i=1}^{N} Q^{2}\left(x,\xi^{i}\right) - \left\{\frac{1}{N}\sum_{i=1}^{N} Q\left(x,\xi^{i}\right)\right\}^{2}$$

Two Stage Supply Chain With Machine Resources



Cardboard Packaging Manufacturer

- 2 stage manufacturing + warehouse
- 13 products, 238 customers
- 8 plants, 9 finishing plants
- 28+93 production lines (machines)
- 3738 transportation channels
- 20912 continuous flow variables
- 140 binary (major) site and (minor) machine variables

Domestic Case Formulation Characteristics

Problem Statistics	*N*=1	*N*=20	*N*=40	*N*=60
Constraints	7,822	156,440	312,880	469,320
- Inequality constraints	3,498	69,960	139,920	209,880
- Equality constraints	4,324	86,480	172,960	259,440
Variables	21,052	418,380	836,620	1,254,860
- Continuous variables	20,912	418,240	836,480	1,254,720
- Integer (binary) variables	140	140	140	140

N = Number of scenarios in master problem

Parameters

- Capacities, supplies, transportation, demand, and costs all log-normally distributed
- 400 Mhz Pentium III, CPLEX 7.0
- 41 seconds for single scenario mean-value deterministic case total cost = 116.115 million

Acceleration Techniques Performance: Quality (Gap)

	Original	1	2	3	4	5
1st Gap	> 100%	31%	> 100%	60%	> 100%	> 100%
10th Gap	60%	8%	40%	5%	60%	9%

	Original	1+2	1+3	1+4	1+5	1+2+3
1st Gap	> 100%	31%	31%	31%	31%	31%
10th Gap	60%	0.7%	0.1%	0.08%	0.5%	0.2%

	Original	2+3	1+3+4	1+2+3+4	1+2+3+5	All
1st Gap	> 100%	60%	31%	31%	31%	31%
10th Gap	60%	3%	0.01%	0.01%	0.06%	0.01%

Acceleration Techniques Performance: Efficiency (Run Time)

N=20

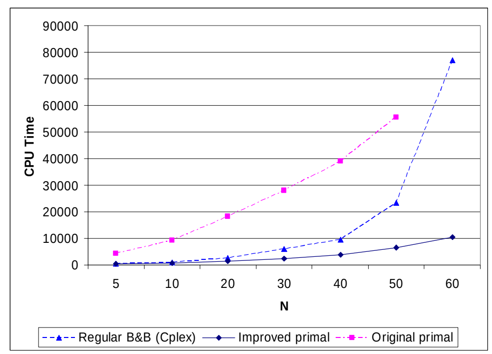
	Original	1	2	3	4	5
Time	> 4,000	> 4,000	> 4,000	> 4,000	> 4,000	> 4,000
Iteration	> 30	> 30	> 30	> 30	> 30	> 30

	Original	1+2	1+3	1+4	1+5	1+2+3
Time	> 4,000	> 4,000	3,860	2,180	> 4,000	3,600
Iteration	> 30	> 30	26	12	> 30	23

	Original	2+3	1+3+4	1+2+3+4	1+2+3+5	All
Time	> 4,000	> 4,000	1,500	1,380	3,050	1,890
Iteration	> 30	> 30	8	7	19	7

Note: The MIP Optimal using CPLEX needs 2,700 seconds

Comparison of Run Times for Solution Algorithms



Stochastic Solutions Robustness for Domestic Case

N=20, M=20, Ní=1000

Configuration	**MPP**	**SS-1**	**SS-2**	**SS-3**
Average obj. value (in million $)	116.77	111.03	111.03	111.05
Max	173.30	122.57	122.08	122.11
Min	99.02	100.38	100.14	100.10
Range	74.28	22.19	21.93	22.01
Standard Deviation	0.34	0.11	0.11	0.11
Absolute Gap	5.91	0.16	0.17	0.18
Relative Gap	0.066574	0.001454	0.001508	0.001619

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Impact of Variability

Problems	Std. Deviation for customer demand	Std. deviation for all other parameters
Medium variability problem	30%	10%
Low variability problem	15%	5%
High variability problem	40%	20%

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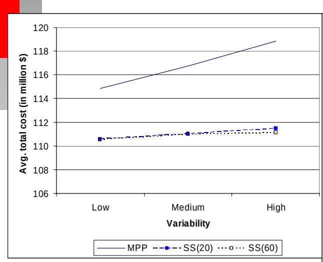
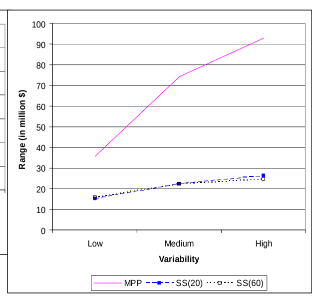
Robustness of Stochastic Solutions for Domestic Case





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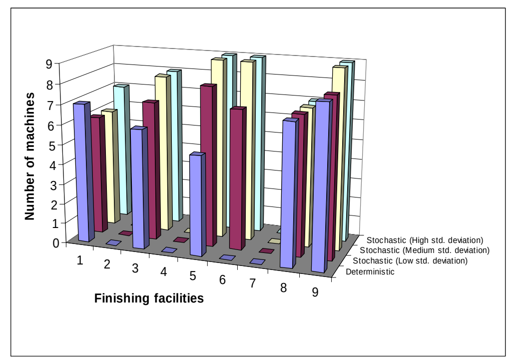
Configurations for Varying Variability



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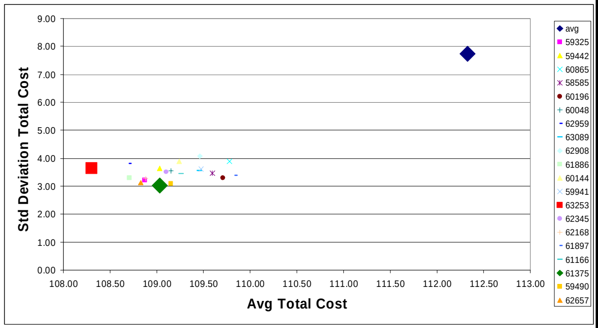
Efficiency Graph For Many Scenarios and Replications



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Global Supply Chain Design

- Net income after tax maximization
- Demand upper bound on sales
- Bill of material (3 levels) flow balance constraints

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Global Case Problem Characteristics

Problem Statistics	*N*=1	*N*=10	*N*=20	*N*=60
Constraints	1,467	14,670	29,340	88,020
- Inequality constraints	402	4,020	8,040	24,120
- Equality constraints	1,065	10,650	21,300	63,900
Variables	6,894	68,310	136,550	409,510
- Continuous variables	6,824	68,240	136,480	409,440
- Integer (binary) variables	70	70	70	70

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Acceleration Techniques Performance: Quality (Gap)

N=20

	Original	1	2	3	4	5
1^{st} Gap	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
50^{th} Gap	41 %	27 %	18 %	21 %	41 %	29 %

	Original	1+2	1+3	1+4	1+5	1+2+3
1^{st} Gap	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
50^{th} Gap	41 %	22 %	12 %	27 %	19 %	3 %

	Original	2+3	1+3+4	1+2+3+4	1+2+3+5	All
1^{st} Gap	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
50^{th} Gap	41 %	5 %	12 %	4 %	< 1 %	< 1 %

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Acceleration Techniques for Benders Decomposition

1. Logistics constraints
   - Echelon capacity, source capacity for average demand
2. Cut disaggregation
   - By scenario
3. Knapsack lower bounds (max. case)
4. Primal feasible heuristic
5. Cut strengthening

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Acceleration Techniques Performance: Efficiency (Run Time)

N=20

	Original	1	2	3	4	5
Time	>13,000	>13,000	>13,000	>13,000	>13,000	>13,000
Iteration	> 60	> 60	> 60	> 60	> 60	> 60

	Original	1+2	1+3	1+4	1+5	1+2+3
Time	>13,000	11,900	>13,000	>13,000	12,300	10,300
Iteration	> 60	56	> 60	> 60	58	51

	Original	2+3	1+3+4	1+2+3+4	1+2+3+5	All
Time	>13,000	>13,000	>13,000	10,300	9,800	9,800
Iteration	> 60	> 60	> 60	51	45	45

Note: The MIP Optimal using CPLEX needs 730,500 seconds)

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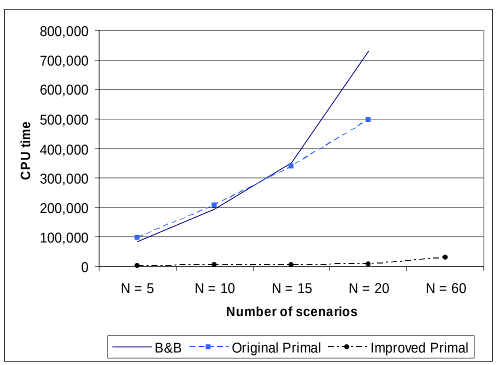
Comparison of Run Times for Solution Algorithms



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Stochastic Solutions Robustness for the Global Case

N=60, M=10, Ní=1000

	MPP	SS
Average NCF	51.021	54.095
Std. Deviation	0.127	0.119
Max NCF	66.996	68.063
Min NCF	31.355	46.531
Range	35.641	21.533
Absolute Gap	3.166	0.092
Relative Gap	0.058425	0.001694

(in million $, except the relative gap)

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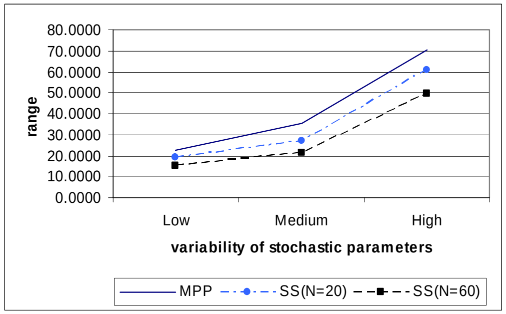
Robustness of Stochastic Solutions for Global Case



Computational Experiment Conclusions: Robustness

- *Designing for average parameters yields a dominated configuration*
  - *Worse mean and standard deviation*
  - *Difference larger for more variable data*
- *More scenarios yield more robust solution (20 to 60 sufficient)*
- *Statistics stable after 500 samples*
- *Report multi-criteria solutions diagram*

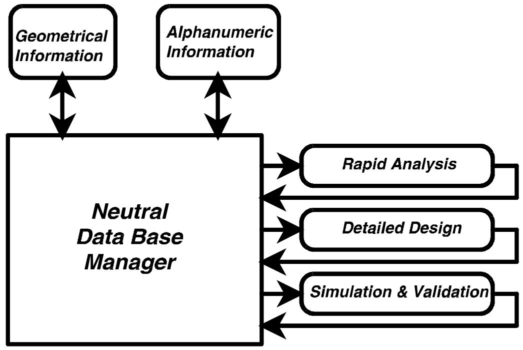
Numerical Experiment Conclusions: Algorithms

- *Significant smaller times for accelerated primal decomposition*
  - *Better than B&B, original primal decomposition*
  - *Dual decomposition worse ??*
- *Combination of acceleration techniques provides time reduction*
- *Bill of Material makes problem much harder to solve*

Conclusions

- *Good definitions and measures for flexibility and robustness are lacking*
- *Current methodology is deterministic design and sensitivity or (few) scenario analysis*
- *Many-scenario solutions are more robust*
- *Only accelerated hierarchical design algorithm fast enough*

CIMPEL Structure



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Strategic Algorithms Toolkit

- LOCAL: heuristic location-allocation
- SMILE: optimal MIP, simple inventory
- NETWORK: optimal material flow for given facilities
- SILAS: optimal NLMIP, stochastic demand and detailed inventory

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Logistics Software Reference

- Andersen Consulting, ìLogistics Software,î jointly with Council of Logistics Management, Oak Brook, IL, 1992 and yearly updates.

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Supply Chain Design Challenges

- Integrated models are large and complex
  - More tactical effects (seasonal, inventory)
- Multi-objective performance measures
  - Cost/profit, flexibility, and responsiveness tradeoffs
- Strategic design as a continuous effort
  - Models, data, algorithms

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Supply Chain Design Challenges Continued

- Technology transfer to logistics professionals and students
  - Toy cases and black-box software

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Supply Chain Modeling Challenges

- Multiple periods, combined with tactical
  - Periodic and seasonal demand
  - Dynamic strategic systems
  - Responsive
- Global
  - Taxes and profit realization
  - Local contents, duty drawback
- Stochastic
  - Flexibility, robustness, risk, scenarios

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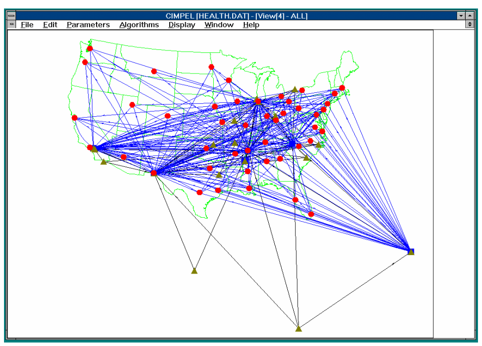
From a Multicommodity Case...



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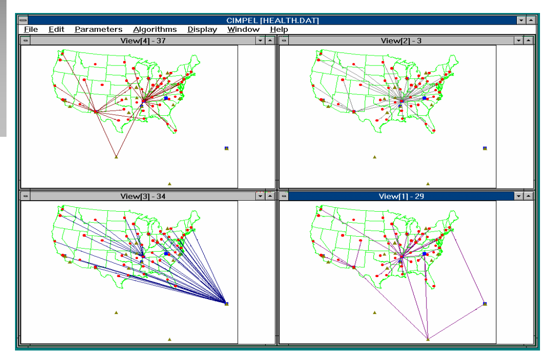
...and Configuration by a Current Design Tool



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