Chapter 5

Network Design in the Supply Chain

1. The Decisions in Network Design:

A Logistics Network consists of:

- **Facilities** (- at the nodes)
  - Vendors, Manufacturing Centers, Warehouse/Distribution Centers, and Customers
- **Flows** (- along the arcs)
  - Raw materials, parts and finished products, etc. that flow between the facilities

**Decisions:** Where? Who? What?

Outline

1. Decisions in network design
2. A strategic framework for logistics network decisions
3. Factors influencing network design
4. Network design tools - major components
5. Solution techniques for network design
   1) Optimizing facility location models
   2) Heuristic approaches
   3) Simulation technique

Network Design - Key issues

**Network setting:**
- Decide the optimal number, location, and size of warehouses and/or plants

**Network operation:**
- Determine optimal sourcing strategy
  - Which plant/vendor should produce which product
- Determine best distribution channels
  - Which warehouses should service which customers...

**The objective:**
- to balance service level against total cost (production, purchasing, inventory, facilities, transportation, handling and processing, etc.)
- to find a minimal-cost configuration of the distribution network that satisfies product demands at specific customer service levels
2. Factors Influencing Network Design Decisions

- Strategic
- Technological
- Macroeconomic
- Political
- Infrastructure
- Competition
- Logistics and facility costs
- ...

3. A framework for network design

- Competitor STRATEGY
- INTERNAL CONSTRAINTS
  - Capital, growth strategy, existing network
- PRODUCTION TECHNOLOGIES
  - Cost, scale/economy of support, required flexibility
- COMPETITIVE ENVIRONMENT
- REGIONAL DEMAND
  - Size, growth, homogeneity, local specifications
- POLITICAL, EXCHANGE RATE AND DEMAND RISK
- AVAILABLE INFRASTRUCTURE
- FACTOR COSTS
  - Labor, materials, site specific
- LOGISTICS COSTS
  - Transport, inventory, coordination

Complexity of Network Design Problems

- Location problems are, in general, very difficult problems (-- NP hard!!)
- The complexity increases with:
  - the number and type of customers,
  - the number and type of products,
  - the number of potential locations for warehouses, and
  - the number of warehouses located
  - ...
- Multi-criteria, uncertainty ..
4. Network Design Tools -- Major Components

- **Mapping**
  - Mapping allows you to visualize your supply chain and solutions
  - Mapping the solutions allows you to better understand different scenarios
  - Color coding, sizing, and utilization indicators allow for further analysis

- **Data analysis**
  - Data specifies the costs of your supply chain
  - The baseline cost data should match your accounting data
  - The output data allows you to quantify changes to the supply chain
  - Aggregation is essential

- **Engine**
  - Solution Techniques

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**Data for Network Design**

1. A listing of all products
2. Location of customers, stocking points and sources
3. Demand for each product by customer location
4. Transportation rates
5. Warehousing costs
6. Shipment sizes by product
7. Order patterns by frequency, size, season, content
8. Order processing costs
9. Customer service goals...

Customers and Geocoding -- **Too Much Information !!!!!!!**

- Sales data is typically collected on a by-customer basis
- Network planning is facilitated if sales data is in a geographic database rather than accounting database
  1. Distances
  2. Transportation costs
- New technology exists for Geocoding the data based on Geographic Information System (GIS)
Testing Customer Aggregation

1 Plant; 1 Product
Considering transportation costs only
Customer data
- Original Data had 18,000 5-digit zip code ship-to locations
- Aggregated Data had 800 3-digit ship-to locations
- Total demand was the same in both cases

Comparing Output - Cost Difference < 0.05% !!!

Total Cost: $5,796,000
Total Customers: 18,000

Total Cost: $5,783,000
Total Customers: 800

Product Aggregation:
- Companies may have hundreds to thousands of individual items in their production line
  1. Variations in product models and style
  2. Some products are packaged in many sizes
- Collecting all data and analyzing it is impractical for so many product groups

Strategies for product aggregation:
- Place all SKU’s into a source-group
  A source group is a group of SKU’s all sourced from the same place(s)
- Within each of the source-groups, aggregate the SKU’s by similar logistics characteristics
  - Weight
  - Volume
  - Holding Cost...

Test Case for Product Aggregation

5 Plants
25 Potential Warehouse Locations
Distance-based Service Constraints
Inventory Holding Costs
Fixed Warehouse Costs
Product Aggregation
- 46 Original products
- 4 Aggregated products
- Aggregated products were created using weighted averages

Aggregation Test: Product Aggregation
-- Cost Difference < 0.03% !!!

Total Cost: $104,564,000
Total Products: 46

Total Cost: $104,599,000
Total Products: 4

5. Solution Techniques for Network Design

1) Mathematical optimization techniques:
   - Exact algorithms: find optimal solutions
2) Heuristics methods:
   - find “good” solutions, not necessarily optimal
3) Simulation models: provide a mechanism to evaluate specified design alternatives created by the designer

Hybrid approaches are often effective!!
5-1) Network Optimization Models

Allocating demand to production facilities
Locating facilities and allocating capacity

Key Costs:
• Fixed facility cost
• Transportation cost
• Production cost
• Inventory cost
• Coordination cost
... Which plants to establish? How to configure the network?

Model (a): Demand Allocation Model

\[
\text{Min } \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij} \\
\text{s.t. } \\
\sum_{i=1}^{n} x_{ij} = D_j \\
\sum_{j=1}^{m} x_{ij} \leq K_i \\
x_{ij} \geq 0
\]

A typical network design problem:
• Several products are produced at several plants.
• Each plant has a known production capacity.
• There is a known demand for each product at each customer zone.
• The demand is satisfied by shipping the products via regional distribution centers.
• There may be an upper bound on total throughput at each distribution center.

Case 1: Demand Allocation at Applichem

<table>
<thead>
<tr>
<th>From</th>
<th>Mexico</th>
<th>Canada</th>
<th>Venezuela</th>
<th>Frankfurt</th>
<th>Gary</th>
<th>Sunchem</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>$81</td>
<td>$92</td>
<td>$136</td>
<td>$101</td>
<td>$96</td>
<td>$101</td>
<td>$220</td>
</tr>
<tr>
<td>Canada</td>
<td>$147</td>
<td>$78</td>
<td>$135</td>
<td>$98</td>
<td>$88</td>
<td>$97</td>
<td>$37</td>
</tr>
<tr>
<td>Venezuela</td>
<td>$172</td>
<td>$106</td>
<td>$96</td>
<td>$120</td>
<td>$111</td>
<td>$117</td>
<td>$45</td>
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<tr>
<td>Frankfurt</td>
<td>$115</td>
<td>$71</td>
<td>$110</td>
<td>$59</td>
<td>$74</td>
<td>$77</td>
<td>$470</td>
</tr>
<tr>
<td>Gary</td>
<td>$143</td>
<td>$77</td>
<td>$134</td>
<td>$91</td>
<td>$71</td>
<td>$90</td>
<td>$185</td>
</tr>
<tr>
<td>Sunchem</td>
<td>$222</td>
<td>$129</td>
<td>$205</td>
<td>$145</td>
<td>$136</td>
<td>$116</td>
<td>$50</td>
</tr>
<tr>
<td>Demand</td>
<td>30</td>
<td>26</td>
<td>160</td>
<td>200</td>
<td>264</td>
<td>119</td>
<td>119</td>
</tr>
</tbody>
</table>

1981 Network (Optimal)

Annual Cost = $79,598,500

Mexico | Canada | Venezuela | Latin America | Europe | U.S.A | Japan
---|---|---|---|---|---|---
Mexico | | | | | | |
Canada | | | | | | |
Venezuela | | | | | | |
Latin America | | | | | | |
Europe | | | | | | |
U.S.A | | | | | | |
Japan | | | | | | |

Annual Cost = $82,246,800
Cash Flows From Sunchem Plant

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal ($ Million)</td>
<td>60.562</td>
<td>68.889</td>
<td>75.999</td>
<td>79.887</td>
<td>79.598</td>
<td>72.916</td>
</tr>
<tr>
<td>Sunchem Closed</td>
<td>60.721</td>
<td>68.889</td>
<td>77.503</td>
<td>80.999</td>
<td>82.247</td>
<td>72.916</td>
</tr>
<tr>
<td>Difference</td>
<td>0.159</td>
<td>0.000</td>
<td>1.504</td>
<td>1.112</td>
<td>2.649</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Value of Adding 0.1 Million Pounds Capacity (1982)

- **Mexico**: $0
- **Canada**: $8,300
- **Venezuela**: $36,900
- **Frankfurt**: $22,300
- **Gary**: $25,200
- **Sunchem**: $0

Should be evaluated as an option and priced accordingly.

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Model (b)
- Plant Location & demand allocation with Multiple Sourcing

\[
\text{Min} \sum_{i=1}^{n} f_i y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij}
\]

- \( y_i = 1 \) if plant is located at site i, 0 otherwise
- \( x_{ij} = \text{Quantity shipped from plant site i to customer j} \)
- \( f_i \) - fixed cost for locating plant at site i
- \( k \) - # of plants to be built/used
- \( K, D \) - constraints on supply and demand

A typical location problem:
- There may be an upper bound on the distance between a distribution center and a market area served by it
- A set of potential location sites for the new facilities was identified
- Costs:
  - Set-up costs
  - Transportation cost is proportional to the distance
  - Storage and handling costs
  - Production/supply costs

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Model (c)
- Plant Location and demand allocation with single Sourcing

\[
\text{Min} \sum_{i=1}^{n} f_i y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} D_j c_{ij} x_{ij}
\]

\[ \sum y_i = 1 \]

\[ \sum_{j=1}^{m} X_{ij} D_j \leq K_i y_i \]

\[ \sum_{i=1}^{n} y_i \leq k \]

\[ x_{ij}, y_i \in \{0,1\} \]

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Model (d)
- Simultaneous plant and warehouse location

Which plants to establish? Which warehouses to establish?

How to configure the network?
Multiple levels facility location - Transshipment model

\[
\begin{align*}
\text{min} & \quad \sum_{i=1}^{n} f_i y_i + \sum_{i=1}^{n} f_i y_i + \sum_{h=1}^{H} \sum_{i=1}^{n} c_{i,h} x_{i,h} + \sum_{h=1}^{H} \sum_{i=1}^{n} c_{i,h} x_{i,h} + \sum_{h=1}^{H} \sum_{i=1}^{n} c_{i,h} x_{i,h} \\
\text{st.} & \quad \sum_{i=1}^{n} x_{i,h} \leq s_h \quad (\text{for all } h) \\
& \quad \sum_{i=1}^{n} x_{i,h} - \sum_{i=1}^{n} x_{i,h} \geq 0 \quad (\text{for all } i) \quad \text{-- Node balancing} \\
& \quad \sum_{i=1}^{n} x_{i,h} \leq K_i, y_i \quad (\text{for all } i) \\
& \quad \sum_{i=1}^{n} x_{i,h} - \sum_{i=1}^{n} x_{i,h} \geq 0 \quad (\text{for all } e) \quad \text{-- Node balancing} \\
& \quad \sum_{i=1}^{n} x_{i,h} \leq w_j y_j \quad (\text{for all } e) \\
& \quad \sum_{i=1}^{n} x_{i,h} = D_j \quad (\text{for all } j) \\
& \quad y_i, x_i \in \{0,1\}
\end{align*}
\]

Gravity Location Model

Model (e) - Gravity Methods for Location

- **Mile-Center Solution**
  - \(x,y\): Warehouse Coordinates
  - \(x_n, y_n\): Coordinates of delivery location \(n\)
  - \(d_n\): Distance to delivery location \(n\)
  - \(D_n\): Annual tonnage to delivery location \(n\)
  \[d_n = \sqrt{(x-x_n)^2 + (y-y_n)^2}\]
  \[x = \frac{\sum_{i=1}^{n} x_i D_i}{\sum_{i=1}^{n} D_i} \]
  \[y = \frac{\sum_{i=1}^{n} y_i D_i}{\sum_{i=1}^{n} D_i} \]

- **Gravity Location Model**
  - **Ton-Center Solution**
    - \(x,y\): Warehouse Coordinates
    - \(x_n, y_n\): Coordinates of delivery location \(n\)
    - \(D_n\): Annual tonnage to delivery location \(n\)
    \[= \text{Focus on distance!!} \]
    \[\text{Min } \sum (x_i-x)^2 + (y_i-y)^2 \]

- **Gravity Location Model**
  - **Ton Mile-Center Solution**
    - \(x,y\): Warehouse Coordinates
    - \(x_n, y_n\): Coordinates of delivery location \(n\)
    - \(d_n\): Distance to delivery location \(n\)
    - \(D_n\): Annual tonnage to delivery location \(n\)
    - \(F_n\): Cost of shipping one unit to location \(n\)
    \[d_n = \sqrt{(x-x_n)^2 + (y-y_n)^2} \]
    \[x = \frac{x_i F_i}{\sum_{i=1}^{n} F_i d_i} \]
    \[y = \frac{y_i F_i}{\sum_{i=1}^{n} F_i d_i} \]

- **Excel File**
  \[\text{Min } \sum F_i D_i \sqrt{(x_i-x)^2 + (y_i-y)^2} \]

- **Look at both distance and tonnage!!**
  \[\text{Min } \sum F_i D_i \sqrt{(x_i-x)^2 + (y_i-y)^2} \]
5-2) Heuristics Methods

Example:
- Single product
- Two plants p1 and p2
- Plant p2 has an annual capacity of 60,000 units.
- The two plants have the same production costs.
- There are two warehouses w1 and w2 with identical warehouse handling costs.
- There are three market areas c1, c2, and c3 with demands of 50,000, 100,000, and 50,000, respectively.

Table 1
Distribution costs per unit

<table>
<thead>
<tr>
<th>Facility</th>
<th>Warehouse</th>
<th>P1</th>
<th>P2</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

The IP model:
\[
\begin{align*}
\text{min} \quad & 0X(p1,w1) + 5X(p1,w2) + 4X(p2,w1) + 2X(p2,w2) + 3X(w1,c1) + 4X(w1,c2) \\
& + 5X(w1,c3) + 2X(w2,c1) + 2X(w2,c3) \\
\text{subject to the following constraints:} \\
& X(p2,w1) + X(p2,w2) \leq 60000 \\
& X(p1,w1) + X(p2,w1) = X(w1,c1) + X(w1,c2) + X(w1,c3) \\
& X(p1,w2) + X(p2,w2) = X(w2,c1) + X(w2,c2) + X(w2,c3) \\
& X(w1,c1) = X(w2,c1) = 50000 \\
& X(w1,c2) = X(w2,c2) = 100000 \\
& X(w1,c3) = X(w2,c3) = 50000 \\
& \text{all flows greater than or equal to zero.}
\end{align*}
\]

Table 2
Distribution strategy

<table>
<thead>
<tr>
<th>Facility</th>
<th>W1</th>
<th>P1</th>
<th>P2</th>
<th>W2</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>140000</td>
<td>0</td>
<td>40000</td>
<td>0</td>
<td>40000</td>
<td>0</td>
<td>50000</td>
</tr>
<tr>
<td>W2</td>
<td>0</td>
<td>40000</td>
<td>0</td>
<td>60000</td>
<td>0</td>
<td>60000</td>
<td>0</td>
</tr>
</tbody>
</table>

The total cost for the optimal strategy is 740,000.

The Heuristics Approach

Heuristic 1:
For each market we choose the cheapest warehouse to source demand. Thus, c1, c2 and c3 would be supplied by w2.
Now for every warehouse choose the cheapest plant, i.e., get 60,000 units from p2 and the remaining 140,000 from p1.
The total cost is:
\[
2 \times 50000 + 1 \times 100000 + 2 \times 50000 \\
+ 2 \times 60000 + 5 \times 140000 = 1,120,000.
\]

Heuristic 2:
For each market area, choose the warehouse such that the total costs to get delivery from the warehouse is the cheapest, that is, consider the source and the distribution.
Thus, for market area c1, consider the paths p1→w1→c1, p1→w2→c1, p2→w1→c1, p2→w2→c1. Of these the cheapest is p1→w1→c1 and so choose w1 for c1.
Similarly, choose w2 for c2 and w2 for c3.
The total cost for this strategy is 920,000.
Why Optimization Matters?

Example:

Traditional Approach #1:
Assign each market to closest WH. Then assign each plant based on cost.

$$\text{Total Costs} = $1,120,000$$

Traditional Approach #2:
Assign each market based on total landed cost

$$\text{Total Cost} = $920,000$$
5-3) Simulation Models

- Optimization techniques deal with static models:
  1. Deal with averages.
  2. Does not take into account changes over time.
- Simulation takes into account the dynamics of the system.
- Simulation models allow for a micro-level analysis:
  1. Individual ordering pattern analysis.
  2. Transportation rates structure.
  3. Specific inventory policies.
  4. Inter-warehouse movement of inventory.
  5. Unlimited number of products, plants, warehouses and customers.

Optimization Techniques vs. Simulation

- The main disadvantage of a simulation model is that it fails to support warehouse location decisions; only a limited number of alternatives are considered.
- The nature of location decisions is that they are taken when only limited information is available on customers, demands, inventory policies, etc, thus preventing the use of micro level analysis.

Recommended approach

- Use an optimization model first to solve the problem at the macro level, taking into account the most important cost components:
  1. Aggregate customers located in close proximity.
  2. Estimate total distance traveled by radial distance to the market area.
  3. Estimate inventory costs using the EOQ model.
- Use a simulation model to evaluate optimal solutions generated in the first phase.

Case 2: Evaluating Facility Investments under Uncertainty —— AM Tires

<table>
<thead>
<tr>
<th>Plant</th>
<th>Dedicated Plant</th>
<th>Flexible Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Cost</td>
<td>Variable Cost</td>
</tr>
<tr>
<td>US 100,000</td>
<td>$1 million/yr.</td>
<td>$15 / tire</td>
</tr>
<tr>
<td>Mexico 50,000</td>
<td>4 million pesos / year</td>
<td>110 pesos / tire</td>
</tr>
</tbody>
</table>

Demand goes up or down by 20 percent with probability 0.5 and exchange rate goes up or down by 25 percent with probability 0.5.
AM Tires

-- scenarios with uncertain demand and exchange rate

Four possible capacity scenarios:
• Both dedicated
• Both flexible
• U.S. flexible, Mexico dedicated
• U.S. dedicated, Mexico flexible

For each scenario solve the demand allocation model.
Integrating Time-in-Transit Data

- Decide the service level required for each lane
- Set outbound rates in model accordingly

BuyPC.com Case Study: Current Network

Inbound: $851,000
Outbound: $2,930,000
Inv Cost: $13,291,000
WH Fixed: $1,875,000
Total: $18,947,000

BuyPC.com Case Study: Cost Trade-Off

Inventory Reduction and Warehouses

- BuyPC.com faced heavy variability in consumer demand
  - Each DC had to carry sufficient safety stock
  - Warehouse to warehouse transfers were discouraged because of the extra liability in shipping computers
- Studies within BuyPC.com indicated that reducing the warehouses would reduce the inventory
  - The Risk Pooling Effect
BuyPC.com Case Study: Optimal Network

- Inbound: $83,000
- Outbound: $5,900,000
- Inv Cost: $7,679,000
- WH Fixed: $625,000
- Total: $14,987,000

$4 Million Savings

Solution result:
- Warehouses picked and sizes
  - Harrisburg 26,000 sq. feet
  - Atlanta 15,000
  - Chicago 18,000
  - Dallas 13,000
  - LA 23,000

BuyPC.com Case Study
Network Design Conclusion and Next Steps

- By reducing the number of warehouses, BuyPC.com could reduce their overall logistics network costs
  - The reduction in inventory costs more than outweighed the increase in next-day air shipments
- But, the strategic network did not consider the impact of seasonality
  - Would they have enough space?
  - When would they have to start building inventory to meet demand?
  - Where would the product be stored?
  - Would the territories change during peak season?

BuyPC.com Demand and Production Capacity

BuyPC.com needed to start building inventory in advance of the Christmas season

What is Tactical Planning?

A tactical plan allows you to develop optimal plan across the supply chain that minimizes transportation costs, inventory costs, and production costs.
**Coordinating Limited Resources**

- **Low Cost**: How do I best use my low cost producers? Which production line do I use for a product?
- **High Cost**: How do I build for the seasonal spike and still meet shelf life restrictions?

Sea, LT = 5 weeks
Air, LT = 4 days

When do we ship air or sea, to minimize in-transit inventory and avoid capacity problems?

**Benefits of Tactical Planning Software**

- **Apply forecasts to the supply chain**: Take your company’s forecast and relate it directly to the supply chain
- **Create better supply chain plans**: Create plans that are optimal across the entire supply chain
- **Analyze different inventory and production strategies**
- **Avoid supply chain bottlenecks**: Anticipate problems months in advance and take action now to alleviate the issue
- **Improved coordination within your supply chain**: Share the output and collaborate with all your supply chain partners to ensure a successful execution of the plan

**What-Ifs with Tactical Planning Software**

- When and where will we run out of capacity
  - Which plant or warehouse? In which month?
- What do we do if we run out of capacity?
  - Should we add capacity? Should we re-align territories?
  - What are the benefits of smoothing out the quarterly demand spikes?
  - How do we meet seasonal demand?
    - Should we build inventory? When to start and where to store?
    - Should we run overtime during the peak months to meet demand?

**Tactical Planning Interface**

Map showing your solution lanes and capacity indicators for September
**Input Data**

- Time Periods
- Customers Information
  - Where you are shipping to and demand by time period
- Plant / Vendor Information
  - Capacity by time period
- Distribution Centers
  - Costs and capacities by time period
- Products
- Transportation Costs
  - The cost to move product from origin to destination

**Output Data**

- Minimum overall total cost
  - Manufacturing costs
  - Warehouse costs (fixed, processing, and inventory)
  - Transportation costs
- Optimal plan for inventory
  - When to produce, where to store, and when to ship
- Appropriate allocation of products to different warehouses
  - By time period
- Optimal production quantity at each manufacturing plant
  - By time period
- Efficient supply channels in the logistics network

**BuyPC.com Tactical Analysis**

- BuyPC.com wanted to minimize the amount of floor space to keep overhead low, yet have enough to handle peak demand
- BuyPC.com wanted to know if their order fulfillment system would have to allow dynamic changing of territories
- The factories in Asia were capacity constrained, so product would have to be brought in early for the peak season

**BuyPC.com Tactical Results:**

Using the size of warehouses calculated by the strategic model, BuyPC can only meet 78% of December’s demand

- In Nov and Dec all warehouses are at capacity and cannot process any more product

- Warehouse Average Inventory Utilization (Volume)

- PA 26,000 → 46,000
- GA 15,000 → 28,000
- IL 18,000 → 24,000
- TX 13,000 → 17,000
- CA 25,000 → 31,000

Increased system sq. feet by over 50%.

But, all demand is satisfied.
With more warehouse space, there is less of a constraint on overall capacity, although several facilities are quite close to the limit. However, space utilization is very poor for the first half of the year.

Alternatively, BuyPC.com could lease space from Oct - Dec in LA (23,000 additional) and PA (26,000). During December, LA would have to ship outside its optimal territory. The order fulfillment system would have to dynamically assign orders to DC's.

Or, BuyPC.com could lease less space from Oct - Dec in LA (15,000 additional) and PA (20,000) and add an additional 25% of production capacity for Sep to Dec. This would also result in less of a seasonal inventory build-up.

BuyPC.com determined that the most economical choice was to lease temporary space, but not increase production.