Transportation Management
Network & Hubs

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Distribution System Approach

Distribution System
- Number and location of transshipment points
- Routes and schedules of vehicles
- Routes and schedules of items flowing

Decisions made at different times
- Strategic – longer scope and less data available (yr+)
- Tactical – shorter scope w/ planning data (week to yr)
- Operational – very short scope real data (daily)
The Network Design Problem

Treat each potential facility location as a node

V V V V V V V V V V

P P P P P P P P P

W W W W W W W W W W

C C C C C C C C C C

C C C C C C C C C C
The Network Design Problem

Treat shipment flows as links or arcs
The Network Design Problem

Network design is the selection of nodes and links that minimize total cost.
Distribution Network Design

Three key questions for Distribution ND

- How many DCs should there be?
- Where should the DCs be located?
- For each SKU and each customer:
  - which DC should serve the customer, and
  - which plant should serve the DC?

Cost & Performance Trade-Offs

- Transportation Costs (Inbound versus Outbound)
- Facility Costs (Fixed versus Throughput)
- Inventory Costs (Cycle versus Safety Stock)
- Customer Service (Availability versus Order Cycle Time)
Facility Location Cost Trade-Offs

- Freight Cost
- Facility Costs
- Inventory Cost
- Total Costs

Number of Warehouses

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A “Simple” MILP Formulation

Minimize: \[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} C_{ijkl} X_{ijkl} + \sum_{k=1}^{K} F_k Z_k \]

Subject to:

\[ \sum_{j=1}^{J} \sum_{k=1}^{K} X_{ijkl} \geq D_{il} ; \text{for all } I \text{ and } L \]
\[ \sum_{k=1}^{K} \sum_{l=1}^{L} X_{ijkl} \leq P_{ij} ; \text{for all } I \text{ and } J \]
\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{l=1}^{L} X_{ijkl} \leq V_k Z_k ; \text{for all } K \]
\[ X_{ijk} \geq 0 , \text{for all } I, J, K \]
\[ Z_k = \{0,1\} , \text{for all } K \]

Where:

\( X_{ijkl} \) = Total annual volume of product \( i \) produced at plant \( j \) and shipped through DC \( k \) on to customer zone \( l \)
\( Z_k = \{0,1\} ; 1 \text{ if the DC at } k \text{ is selected, else } 0 \)

\( D_{il} \) = annual demand for product \( i \) at customer zone \( l \)
\( P_{ij} \) = maximum annual capacity for product \( i \) at plant \( j \)
\( V_k \) = maximum annual throughput volume at DC at \( k \)
\( F_k \) = The fixed annual operating cost of a DC at \( k \)
\( C_{ijkl} \) = The variable cost to produce one unit of product \( i \) at plant \( j \) and ship it through DC \( k \) to customer zone \( l \) so that \( C_{ijkl} = C[mnfg]_{ij} + \text{TL}_{ijk} + D\text{CHPT}_{ik} + \text{LTL}_{ikl} \)

How big is this formulation?

20 Plants, 30 Products/ Product Groups, 50 Potential DCs, and 400 Customers
Regions, there are:

12,000,000 possible flows!
A “Better” MILP Formulation

Minimize: \[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} A_{ijk} X_{ijk} + \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{l=1}^{L} B_{ikl} Y_{ikl} + \sum_{k=1}^{K} F_k Z_k \]

Subject to:

1. \[ \sum_{k=1}^{K} Y_{ikl} \geq D_{il} \text{ for all I and L} \]
2. \[ \sum_{k=1}^{K} X_{ijk} \leq P_{ij} \text{ for all I and J} \]
3. \[ \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ijk} \leq V_k Z_k \text{ for all K} \]
4. \[ \sum_{j=1}^{I} \sum_{i=1}^{I} X_{ijk} \geq \sum_{l=1}^{L} Y_{ikl} \text{ for all I and K} \]
5. \[ X_{ijk} \geq 0; \text{ for all I, J, K} \]
6. \[ Y_{ikl} \geq 0; \text{ for all I, K, L} \]
7. \[ Z_k = \{0,1\}; 1 \text{ if the DC k is selected, else 0} \]

Where:

- \( X_{ijk} \) = Total annual volume of product i produced at plant j and shipped through DC k
- \( Y_{ikl} \) = Total annual volume of product i shipped from DC k to customer zone l
- \( Z_k \) = \{0,1\}; 1 if the DC k is selected, else 0
- \( A_{ijk} \) = The variable cost to produce one unit of product i at plant j and ship it to the DC at k
- \( B_{ikl} \) = The variable cost to move one unit of product i through the DC at k and ship it to the customer zone at l
- \( D_{il} \) = annual demand for product i at customer zone l
- \( P_{ij} \) = maximum annual capacity for product i at plant j
- \( V_k \) = maximum annual throughput volume at DC at k
- \( F_k \) = The fixed annual operating cost of a DC at k

How big is this formulation?

20 Plants, 30 Products/ Product Groups, 50 Potential DCs, and 400 Customers Regions, there are:

50,000 (30k IB & 20k OB) possible flows
Issues & Concerns

Data Issues
- Demand Point Aggregation
- Demand over Time Periods
- Profiling freight cost data
- Fixed Costs: Periodic versus One-Time
- Cost Estimating Functions

Global Extensions
- Freight Rate Availability
- Transfer Prices and Taxes
- Exchange Rates
- Duty and Duty Drawback

Missed Questions
- What about Inventory?
- What about Customer Service?
- Supply Chain Extensions
Inventory Deployment

何安全库存应该在每个DC拥有？

![公式]

\[
ICC_{ij} = COG_i \times ICC\%_{ij} \times SS_{ij}
\]

- **Inventory Carrying Cost for SKU_i at DC_j**
- **Inventory Carrying Cost %**
- **Cost of Goods Sold**

**Why is this difficult?**

- **SS_{ij} = K_i \sqrt{\sigma^2_{D_{ij}} L_{ij} + \sigma^2_{L_{ij}} D^2_{ij}}**
  - **Safety Stock for SKU_i @ DC_j**
  - **Fill rate adjustment by SKU by Customer**
  - **Std Dev of Supplier Lead time**
  - **Average Demand**
  - **Std Dev of Demand**
  - **Average Supplier Lead Time**
Transportation Networks

- One to Many w/o Transshipment
- One to Many w/ Transshipment (why?)
- Many to Many
  - w/o Transshipment
    - Direct
    - Multi-Stop
  - w/ Transshipment (Hub)
    - Directs
    - Multi-Stops
Many to Many Networks

How should I ship from 5 origins to 5 destinations?

Direct Network
Many to Many Networks

How should I ship from 5 origins to 5 destinations?

Hub & Spoke Network
Direct versus Hub

Which is better?
- How many trucks are needed?
- What is the cost?
- How can I increase frequency of service?

Example Details
- Need to pick up every day from terminals
- Average distance between terminals = 500 miles
- Average distance from terminals to hub = 350 miles
- Cost for transportation = $200 shipment + 1 $/mile
Hub versus Direct

How does demand impact?
- Daily demand from terminal $i$ to $j$ is $\sim N(100, 30)$
- Suppose break even for a TL move is 50 units.

Variability

Direct Network
- What is the:
  - Average quantity per move?
  - Standard deviation of load per move?
  - Coefficient of Variation per move?
- What is the frequency of moves that lose money?

Hub Network
- What is the:
  - Average quantity per move?
  - Standard deviation of load per move?
  - Coefficient of Variation per move?
- What is the frequency of moves that lose money?
Hub Advantages

- Hub consolidation reduces costs
  - Consolidation increases conveyance utilization
  - Transportation has a fixed (per conveyance) cost
- Fewer conveyances are required
  - Is consolidation better . . .
    - when point to point demand is higher or lower?
    - when variability of point to point demand is higher or lower?
  - Coefficient of variation as useful metric
- Provides better level of service with fewer resources
  - Non-stop vs. frequency of service
  - Non-stop vs. geographical coverage
    - serving more / smaller cities
Hub Disadvantages

- **Cost of operating the hub**
  - Facility costs
  - Handling costs - unloading, sorting, loading
  - Opportunity for misrouting, damage, theft (shrinkage)

- **Circuity**
  - Longer total distance travelled
  - More vehicle-hours expended

- **Impact on service levels**
  - Added time in-transit
  - Lower reliability of transit

- **Productivity/utilization loss**
  - Cycle/”bank” size
Hub Economics

- Relative distances
  - Degree of circuity
- Vehicle and shipment size
  - Smaller shipments → hub more economical
- Demand pattern
  - Many destinations from each origin
  - Many origins into each destination
- The hub location
  - Significant business generation for passengers
    - Air – large city
    - Transit – CBD
  - Good access for freight
    - Highways access
    - Away from population centers
Terminal Bypass Operations

When would you want to bypass hub handling?

Examples

- Air - through flight
  - Use heaviest pair
  - Marketing; reliability; lower costs
- LTL - “head loading”
- Rail - block placement
- Parcel - pre-packaging

Packages physically travel to the hub, but are not touched or handled.
Directs in a Hub-and-Spoke Network

Considerations in setting direct service:
- Demand between E1 and W2
- Service E1-Hub and Hub-W2
- Effect on the hub
- Effect on E1 activities

For freight services:
- Dynamic ("opportunistic")
- Direct services ("surge move")
- Planned ("multiple offerings")
Regional Terminals

What if there is demand between the W terminals?
Regional Terminals

Diagram showing connections between regional terminals.
Bypassing the Hub
More Routing Alternatives
More Routing Alternatives

Routings:
• W5-W-E5
• W5-H-E5
• W5-E-E5
• W5 – E5

Direct effects:
• On each of the three alternatives

Indirect effects:
• Congestion and spill-overs
Strategic Network

Service Offerings from W5 to E5

- Central Hub Routing
- Regional Terminal Routing
- Direct Routing

Central Hub: 3 days, $100
West/East Hub: 2 days, $120
Direct: 1 day, $200
Location Pooling

**Situation**
- Region has 3 sales/delivery teams
- Each team has its own territory
- Each team has its own inventory site
- Daily demand ~N(15, 4) within each territory
- Lead time to each territory site = 2 days
- Cycle service level set at 99.9%

**How much safety stock should be in each territory?**

**What if they pool to a common site?**
- Assume same lead time and CSL
Location Pooling

Note declining marginal benefit of pooling

- Going from 1 to 3 – reduced SS by 42%
- Going from 7 to 9 – reduced SS by 12%

Good or bad?

Issues?

Concerns?
Location Pooling

Recall the impact on cycle stock as well . . .

- Impact on replenishment to the DC location
- Other impacts?

\[ Q^* = \sqrt{\frac{2AD}{vr}} \]

\[ \overline{IOH} = \frac{Q^*}{2} \quad TRC^* = \sqrt{2DAvr} \]

\[ q_i^* = \sqrt{\frac{2Ad_i}{vr}} = \sqrt{\frac{2AD}{vrvn}} \]

\[ \overline{IOH} = \sum_{i=1}^{n} \left( \frac{q_i^*}{2} \right) = \sqrt{n} \left( \frac{Q^*}{2} \right) \]

\[ TRC^* = \sqrt{2nDAvr} \]
Lead Time Pooling

Types of Uncertainty Faced
- Total demand uncertainty
- Allocation demand uncertainty
- Product mix uncertainty

Consolidated Distribution
- Keep inventory near customers
- Hedge against allocation uncertainty

Adapted from Cachon & Terwiesch 2005
Lead Time Pooling

**Situation**
- Vendor direct shipments to 100 retail stores
- 4 week replenishment lead time
- 4 week review period at store
- Stores use (R,S) policy for inventory
- Weekly demand in each store is iid \( \sim \text{N}(75, 20) \)
- IFR = 99.5%

**What is the safety stock on hand in the system?**

**Other concerns?**
Lead Time Pooling

Proposed Situation
- Vendor direct shipments to 100 retail stores
- 4 week replenishment lead time Vendor to RDC
- 1 week replenishment lead time RDC to Stores
- Stores & RDC use (R,S) policy for inventory
- 4 week review period at RDC (4 or 1 week R at stores)
- Weekly demand in each store is iid ~N(75, 20)
- IFR = 99.5% at RDC and Stores

What is the safety stock on hand in the system?
What would happen if R=1 for stores?
Who owns the pipeline inventory?
Flow Strategies / Profiles

- Multiple Patterns to Flow Product
  - Direct Vendor to Customer
  - Direct Vendor to Store (DSD)
  - Vendor to RDC to Store

- Which pattern is ‘the best’?

- Should I only have one flow pattern?
# Network Structure Tradeoffs

<table>
<thead>
<tr>
<th>Structure</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Shipping</td>
<td>✈️ No intermediate DCs</td>
<td>✈️ Large lot sizes (high inventory levels)</td>
</tr>
<tr>
<td></td>
<td>✈️ Simple to coordinate</td>
<td>✈️ Large receiving expense</td>
</tr>
<tr>
<td>Direct w/ Milk Runs</td>
<td>✈️ Lower transport costs for smaller shipments</td>
<td>✈️ Increased coordination complexity</td>
</tr>
<tr>
<td></td>
<td>✈️ Lower inventory levels</td>
<td></td>
</tr>
<tr>
<td>Direct w/ Central DC (holding inventory)</td>
<td>✈️ Lower IB transport costs (consolidation)</td>
<td>✈️ Increased inventory costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✈️ Increased handling at DC</td>
</tr>
<tr>
<td>Direct w/ Central DC (X-dock)</td>
<td>✈️ Very low inventory requirements</td>
<td>✈️ Increased coordination complexity</td>
</tr>
<tr>
<td></td>
<td>✈️ Lower IB transport costs (consolidation)</td>
<td></td>
</tr>
<tr>
<td>DC w/ Milk Runs</td>
<td>✈️ Lower OB transport costs for smaller shipments</td>
<td>✈️ Further increase in complexity</td>
</tr>
<tr>
<td>Hybrid System</td>
<td>✈️ Best fit of structure for business</td>
<td>✈️ Exceptionally high level of complexity for planning and execution</td>
</tr>
<tr>
<td></td>
<td>✈️ Customized for product, customer mix</td>
<td></td>
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</tbody>
</table>
Network Structure Drivers

<table>
<thead>
<tr>
<th></th>
<th>Short Distance</th>
<th>Medium Distance</th>
<th>Long Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Density</td>
<td>Pvt fleet with milk runs</td>
<td>X-dock with milk runs</td>
<td>X-dock with milk runs</td>
</tr>
<tr>
<td>Medium Density</td>
<td>Third Party Milk Runs</td>
<td>LTL Carrier</td>
<td>LTL or Package Carrier</td>
</tr>
<tr>
<td>Low Density</td>
<td>Third Party Milk Runs or LTL Carrier</td>
<td>LTL or Package Carrier</td>
<td>Package Carrier</td>
</tr>
</tbody>
</table>

Customer density versus Length of Haul

<table>
<thead>
<tr>
<th></th>
<th>High Value Product</th>
<th>Low Value Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Demand</td>
<td>Disaggregate cycle inventory</td>
<td>Disaggregate all inventory</td>
</tr>
<tr>
<td></td>
<td>Aggregate safety stock</td>
<td>Inexpensive transport for replenishment</td>
</tr>
<tr>
<td></td>
<td>Inexpensive transport for cycle replenishment</td>
<td>Inexpensive transport for replenishment</td>
</tr>
<tr>
<td></td>
<td>Fast transport for safety stock</td>
<td></td>
</tr>
<tr>
<td>Low Demand</td>
<td>Aggregate all inventory</td>
<td>Aggregate only safety stock</td>
</tr>
<tr>
<td></td>
<td>Fast transport for customer orders</td>
<td>Inexpensive transport for replenishment</td>
</tr>
</tbody>
</table>

Demand versus Product Value

Source: Chopra & Meindl 2004
Questions, Comments?