Logistic Network Design For Closed – Loop Supply Chains

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Overview

- Research Framework
- Motivation and Definitions
- Customer Driven Network Design
  - Product Lifecycle Influences
  - Value and Impact of Bidirectional Decision Frameworks
- Firm Driven Network Design
  - Modeling Distance Sensitivity
  - Profit-Driven and Compliance-Driven Models
- Future Research
Returns

Sources

- Customer driven (commercial returns, quality issues)
- Firm driven (value recovery, legislation, competition)

Operational Impact

Many industries suffer from high return rates

Financial Impact

- Estimated U.S. value = $100B annually
- 0.5 – 1.0% U.S. GDP
Research Framework

Forward Logistics

- Raw Materials
- Parts Production
- Assembly
- Distribution
- Consumer

Reverse Logistics

- Landfill
- Recycling
- Remanufacturing
- Refurbishing
- Reuse
# Research Framework

<table>
<thead>
<tr>
<th>Problem level</th>
<th>Strategic</th>
<th>Tactical</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Return type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firm driven</td>
<td>Distribution network design</td>
<td>Capacity planning</td>
<td>Production planning / scheduling</td>
</tr>
<tr>
<td></td>
<td>Customer Behavior Influenced CLSC Network Design</td>
<td>Inventory management</td>
<td>Demand / Return forecasting</td>
</tr>
<tr>
<td>Consumer driven</td>
<td>Integrated Bidirectional Network Design</td>
<td>Lifetime Buys in Warranty Repair Operations</td>
<td></td>
</tr>
</tbody>
</table>
Research Framework
Research Questions

What is the **VALUE** and **IMPACT** of integrating forward and reverse network decisions throughout the product lifecycle?

in various industries?
Life Cycle Considerations

- **Introductory Stage**
  - Forward Dominant Model
  - Co-Location Model

- **Maturity Stage**

- **Decline Stage**
  - Commercial Returns
  - Reverse Dominant Model
  - End of Life Returns

- **Product Demand**
Integrated Bi-Directional Networks

- Integrated by location constraints
- Integrated by financial incentives

Forward Dominant Model

Reverse Dominant Model

Co-Location Model

Demand node

Forward flow

Reverse flow
Model Development

Recall the Uncapacitated Fixed Charge Problem (UFC):
Forward Dominant Model

Case: Retail Returns

Minimize
\[
\sum_{j \in J} f_j X_j^F + \sum_{i \in I} \sum_{j \in J} h_{ij} c_{ij} Y_{ij}^F + \sum_{j \in J} \beta_j f_j X_j^R + \sum_{i \in I} \sum_{j \in J} \alpha_i h_{ij} \gamma_{ij} c_{ij} Y_{ij}^R
\]

Subject to
\[
\sum_{j \in J} Y_{ij}^F = 1 \quad \sum_{j \in J} Y_{ij}^R = 1 \quad \forall i \in I \quad \text{assignment}
\]
\[
Y_{ij}^F \leq X_j^F \quad Y_{ij}^R \leq X_j^R \quad \forall i \in I, j \in J \quad \text{open facilities}
\]
\[
X_j^F = \{0,1\} \quad X_j^R = \{0,1\} \quad \forall j \in J \quad \text{binary}
\]
\[
Y_{ij}^F \geq 0 \quad Y_{ij}^R \geq 0 \quad \forall i \in I, j \in J \quad \text{non-negativity}
\]
\[
X_j^F \geq X_j^R \quad \forall j \in J \quad \text{linking}
\]

Solve using Lagrangian Relaxation
Reverse Dominant Model

Case: Recycling Networks

Minimize

\[
\sum_{j \in J} \gamma_j X_j^F + \sum_{i \in I} \sum_{j \in J} h_i c_{ij} Y_{ij}^F + \sum_{j \in J} \beta_j \gamma_j X_j^R + \sum_{i \in I} \sum_{j \in J} \alpha_i h_i \gamma_{ij} c_{ij} Y_{ij}^R
\]

Subject to

\[
\begin{align*}
\sum_{j \in J} Y_{ij}^F &= 1 & \forall i \in I \\
\sum_{j \in J} Y_{ij}^R &= 1 & \forall i \in I \\
Y_{ij}^F &\leq X_j^F & \forall i \in I, j \in J \\
Y_{ij}^R &\leq X_j^R & \forall i \in I, j \in J \\
X_j^F &= \{0,1\} & \forall j \in J \\
X_j^R &= \{0,1\} & \forall j \in J \\
Y_{ij}^F &\geq 0 & \forall i \in I, j \in J \\
Y_{ij}^R &\geq 0 & \forall i \in I, j \in J \\
X_j^F &\leq X_j^R & \forall j \in J
\end{align*}
\]

Reverse Dominant Model
Co-location Incentive Model

Case: Combined Commercial & End of Life Returns Handling

Minimize

$$\sum_{j \in J} f_j X_j^F + \sum_{i \in I} \sum_{j \in J} h_i c_{ij} Y_{ij}^F + \sum_{j \in J} \beta_j f_j X_j^R + \sum_{i \in I} \sum_{j \in J} \alpha_i h_i \gamma_{ij} c_{ij} Y_{ij}^R - \sum_{j \in J} s_j^C X_j^C$$

Subject to

$$\sum_{j \in J} Y_{ij}^F = 1 \quad \sum_{j \in J} Y_{ij}^R = 1 \quad \forall i \in I$$ assignment

$$Y_{ij}^F \leq X_j^F \quad Y_{ij}^R \leq X_j^R \quad \forall i \in I, j \in J$$ open facilities

$$X_j^F = \{0, 1\} \quad X_j^R = \{0, 1\} \quad \forall j \in J$$ binary

$$Y_{ij}^F \geq 0 \quad Y_{ij}^R \geq 0 \quad \forall i \in I, j \in J$$ non-negativity

$$X_j^F \geq X_j^C \quad X_j^R \geq X_j^C \quad \forall j \in J$$ linking

$$X_j^C = \{0, 1\} \quad \forall j \in J$$
Non-Integrated Design

Forward Dominant Model
Sequential Design
Non-Integrated Design

Reverse Dominant Model
Sequential Design

All candidate sites

Reverse sites

Forward sites
Non-Integrated Design

Co-Location Model
Independent Design

All candidate sites

Forward sites

Reverse sites
Similarity Measure

Solution 1
3 out of 4 common locations

Solution 2
0 out of 4 common locations

Solution 3
Similarity Measure

Solution 1

Solution 2

3 of 4 locations in common

Total difference between solutions (in miles) = 2153

New York 0 New York
Chicago 0 Chicago
Los Angeles 2153 Jacksonville
Houston 0 Houston
Similarity Measure

0 of 4 locations in common
Total difference between solutions (in miles) = 190
- New York ← 81 → Allentown
- Chicago ← 86 → Milwaukee
- Los Angeles ← 7 → Burbank
- Houston ← 16 → Pasadena
Similarity Measure

Minimal Distance Matching Formulation

Minimize \[ \sum_{i \in X_m} \sum_{j \in X_n} c_{ij} Y_{ij} \]
Subject to \[ \sum_{i \in X_m} Y_{ij} \geq 1 \quad \forall j \in X_n \]
\[ \sum_{j \in X_n} Y_{ij} \geq 1 \quad \forall i \in X_m \]
\[ Y_{ij} \geq 0 \quad \forall i \in X_m \quad \forall j \in X_n \]

Solution Method: Modified Out of Kilter Flow Algorithm

normalize to get similarity ratio = \[ \frac{\sum_{i \in X_m} \sum_{j \in X_n} c_{ij} Y_{ij}}{\max_{(i,j)} c_{ij}} \]
## Results

<table>
<thead>
<tr>
<th>Model</th>
<th>Data Set</th>
<th>Value of Integration</th>
<th>Forward Similarity ratio</th>
<th>Reverse Similarity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
<td>Average</td>
</tr>
<tr>
<td>Forward Dominant</td>
<td>150 nodes</td>
<td>2.42%</td>
<td>30.07%</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>263 nodes</td>
<td>6.02%</td>
<td>28.59%</td>
<td>0.15</td>
</tr>
<tr>
<td>Reverse Dominant</td>
<td>150 nodes</td>
<td>0.08%</td>
<td>4.64%</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>263 nodes</td>
<td>0.10%</td>
<td>1.69%</td>
<td>0.06</td>
</tr>
<tr>
<td>Co-Location</td>
<td>150 nodes</td>
<td>0.60%</td>
<td>2.48%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>263 nodes</td>
<td>1.41%</td>
<td>3.87%</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Extensions

Time Integrated Models

Multiple Products with Overlapping Lifecycles

Customer Behavior Based Networks
Customer Behavior - Based Networks

Applicable to:

- Single use cameras (Kodak)
- Copy Print cartridges (Cartridge World)
- Mobile Phones (Recellular)
- Hard Drives (3P Remanufacturers)
- Medical Equipment
Distance-Sensitive Customers
Distance-Sensitive Customers

Demand decays exponentially with distance

Demand at node $i$ served by facility $j$ ($h_{ij}$):

$$h_{ij} = h_i e^{-\lambda_i d_{ij}}$$

- $h_i$ = total demand at node $i$
- $\lambda_i$ = decay factor (distance sensitivity) at node $i$
- $d_{ij}$ = distance between node $i$ and facility $j$
- $h_{ij}$ = demand at node $i$ served by facility $j$

$h_i = 100$
$\lambda_i = 0.25$

$d_{ij} = 8 \quad h_{ij} = 13.5$
$d_{ik} = 3 \quad h_{ik} = 47.2$
$d_{im} = 15 \quad h_{im} = 2.4$

Total: 63.1
Capturing “Lost Demand”

Define an “area of interest” / maximum area of consideration

critical distance = 10

\[ h_i = 100 \]
\[ \lambda_i = 0.25 \]
\[ d_{ij} = 8 \quad s_{ij} = 1 \quad h_{ij} = 13.5 \]
\[ d_{ik} = 3 \quad s_{ik} = 1 \quad h_{ik} = 47.2 \]
\[ d_{im} = 15 \quad s_{im} = 0 \quad h_{im} = 0 \]

Total: \[ 60.7 \]
Distance-Sensitive Customers

Capturing “lost demand” in a discrete location model

\[ p_{ij} = \frac{X_j \times s_{ij} \times e^{-\lambda d_{ij}}}{\sum_{k \in J} X_k \times s_{ik} \times e^{-\lambda d_{ik}}} \]

Add “lost demand facility” at border
Profit Maximizing Model

Max \( r \sum_{i \in I} \sum_{j \in \{J \setminus 0\}} h_i p_{ij} - \sum_{j \in \{J \setminus 0\}} f_j X_j - \sum_{i \in I} \sum_{j \in \{J \setminus 0\}} c_{ij} h_i p_{ij} \)

Revenue from satisfied demand
Fixed location costs
Variable transportation costs

Subject to

\( X_0 = 1 \)

“Lost Demand”
Facility is Open

\( X_j \in \{0,1\} \)
\( \forall j \in J \)

Binary location variables

Non–Linear Integer Formulation

This model can be effectively solved using a genetic algorithm heuristic
Demand Maximizing Model

Max \[ r \sum_{i \in I} \sum_{j \in J \setminus \{0\}} h_i p_{ij} \]

Subject to \[ \sum_{j \in J} X_j = P \]

\[ X_0 = 1 \]

\[ X_j \in \{0,1\}, \quad \forall j \in J \]

Revenue from satisfied demand

Locate P Facilities

“Lost Demand” Facility is Open

Binary location variables
Example

Logistic Network Design For Closed – Loop Supply Chains

Maximize Satisfied Demand

<table>
<thead>
<tr>
<th># facilities</th>
<th>% covered demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 5</td>
<td>77.8%</td>
</tr>
<tr>
<td>N = 10</td>
<td>94.5%</td>
</tr>
<tr>
<td>N = 15</td>
<td>99.6%</td>
</tr>
<tr>
<td>N = 2</td>
<td>44.8%</td>
</tr>
</tbody>
</table>

Maximum distance 300 miles
Distance decay factor 0.005
263 largest US cities

USA Data Set

N = 15
99.6%
A CLSC Model with Distance-Sensitive Demand and Returns

Max

\[ r^F \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} h_i^F p_{ij}^F + r^R \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} h_i^R p_{ij}^R \]

\[ - \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} f_j^F x_j^F - \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} f_j^R x_j^R \]

\[ - \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} c_{ij}^F h_i^F p_{ij}^F - \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} c_{ij}^R h_i^R p_{ij}^R \]

Subject to

\[ \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} h_i^R p_{ij}^R > \alpha \sum_{i \in I} \sum_{j \in \{J \setminus \emptyset\}} h_i^F p_{ij}^F \]

\[ x_0^F, x_0^R = 1 \]

\[ x_j^F, x_j^R \in \{0,1\} \quad \forall j \in J \]

Revenue from satisfied demand & collected returns

Fixed location costs

Variable transportation costs

Collect at least \(\alpha\)% of sold items

“Lost Demand” Facility is Open

Binary location variables
Extensions

Other Mechanisms to Influence Customer Return Behavior:

- Future purchase incentives (mobile phones)
- Cash Redemption / Payments / Deposit-Refund

Future Research

- Bounding & exact solution methods
- Integrate other customer behavior models into CLSC network design problems \( (MCI \ & \ MNL \ models) \)
Questions?