The Design of Capacitated Intermodal Hub Networks with Different Vehicle Types

Elif Zeynep Serper
Department of Industrial Engineering
TOBB University of Economics and Technology
ezserper@etu.edu.tr

Sibel A. Alumur
Department of Management Sciences
University of Waterloo
sibel.alumur@uwaterloo.ca

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Agenda

- Introduction
- Problem Definition
- Mathematical Model
- Local Search Heuristic
- Computational Analysis
- Conclusions
Hubs

- Special facilities that serve as switching, transshipment, and sorting points in many-to-many distribution systems

- Economies of scale
Hubs
Hub Location Problem

- Find the location of hub facilities
- Allocate demand nodes to hubs
  - Single Allocation
  - Multiple Allocation
- Hub location literature
  Location analogous problems:
  - $p$-hub median,
  - hub location with fixed costs,
  - $p$-hub center,
  - hub covering problems
Classical Hub Location Problems

- **p-hub median problem**

- **Hub location problem with fixed costs**
  - O'Kelly (1992)
  - Uncapacitated and capacitated variants

- **p-hub center problem**

- **Hub covering problems**

- **Reviews and overviews**

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**Objective Function:**

\[
\text{Min} \sum_{i \in N} \sum_{j \in N} w_{ij} \left( \sum_{k \in N} c_{ik} x_{ik} + \alpha \sum_{k \in N} \sum_{l \in N} c_{kl} x_{ik} x_{jl} + \sum_{l \in N} c_{lj} x_{jl} \right)
\]

**Constraints:**

1. \( \sum_{k \in N} x_{ik} = 1 \quad \forall i \in N \) (1)
2. \( x_{ik} \leq x_{kk} \quad \forall i, k \in N \) (2)
3. \( \forall k \in N \)
4. \( x_{ik} \in \{0,1\} \quad \forall i, k \in N \) (4)
Basic Assumptions

1. The hub network is complete with a direct link between every hub pair

2. There is economies of scale incorporated by a discount factor (usually referred to as $\alpha$) for using the inter-hub connections

3. No direct service (between two non-hub nodes) is allowed
Hub network is not complete!

In Turkey:
- Yurtiçi Cargo
- MNG Cargo
- Aras Cargo

In the world:
- UPS
- FedEx
- DHL
Hub location and hub network design

- Multiple allocation minimizing total costs

- Hub arc location problems
  - Campbell et al. (2005)

- Tree of hubs location problem
  - Contreras et al. (2010)

- Incomplete hub covering problems
  - Alumur and Kara (2009), Calik et al. (2009)

- Single allocation hub network design
  - Alumur et al. (2009)

- Hierarchical hub network design
  - Yaman (2009), Alumur et al. (2012)
Real-life parcel delivery
Decisions to be made

- Locations and capacities of hubs
- Transportation modes to serve at hubs
- Allocation of non-hub nodes to hubs
- Number of vehicles of each type to operate on the hub network
- Routes of the demand between origin-destination pairs
Hub location and hub network design
Nickel et al. (2001), Campbell et al. (2005), Yoon and Current (2008), Alumur et al. (2009), Contreras et al. (2010), Alumur et al. (2015), Martins de Sa et al. (2015)

Hub location in intermodal transportation networks
Racunica and Wynter (2005), Limbourg and Jourquin (2009), Ishfaq and Sox (2011)

Hub location and intermodal hub network design
Meng and Wang (2011), Alumur et al. (2012a, 2012b)
Problem definition
Problem definition

Assumptions:

1. 
2. 
3. 
4. Each vehicle operates on a single connection
Mathematical model

Sets:

\( N \) : Set of demand nodes

\( H \) : Set of potential hub nodes

\( Q \) : Set of hub capacities

\( M \) : Set of transportation modes

\( V \) : Set of vehicle types

\( V_m \) : Set of vehicle types that can use transportation mode \( m \in M \) \((V_m \in V)\)
### Mathematical model - Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{ij}$</td>
<td>Amount of flow originated at node $i \in N$ destined to node $j \in N$.</td>
</tr>
<tr>
<td>$c_{ij}$</td>
<td>Unit cost of transportation from node $i \in N$ to hub $j \in H$ on allocation connections.</td>
</tr>
<tr>
<td>$c_{ij}^v$</td>
<td>Unit cost of transportation from hub $i \in H$ to hub $j \in H$ using vehicle of type $v \in V$.</td>
</tr>
<tr>
<td>$f_{Cj}$</td>
<td>Fixed cost of establishing a hub at node $j \in H$.</td>
</tr>
<tr>
<td>$k_{cm}^{m_{jq}}$</td>
<td>Cost of installing capacity $q \in Q$ for transportation mode $m \in M$ at a hub established at node $j \in H$.</td>
</tr>
<tr>
<td>$k_q^v$</td>
<td>Maximum number of vehicles of type $v \in V$ that a hub with capacity $q \in Q$ can handle.</td>
</tr>
<tr>
<td>$u^v$</td>
<td>Capacity of a vehicle of type $v \in V$.</td>
</tr>
<tr>
<td>$o^v$</td>
<td>Number of owned vehicles of type $v \in V$.</td>
</tr>
<tr>
<td>$oc^v$</td>
<td>Operational cost of a vehicle of type $v \in V$.</td>
</tr>
<tr>
<td>$rc^v$</td>
<td>Renting cost of a vehicle of type $v \in V$.</td>
</tr>
</tbody>
</table>
Mathematical model - Parameters

\( mhc_j \)  
Material handling cost of one unit of flow arriving from a demand node to hub \( j \in H \).

\( mhc^m_j \)  
Material handling cost of one unit of flow arriving with transportation mode \( m \in M \) to hub \( j \in H \) from another hub.

\( a_i \)  
Number of vehicles required to transport the flow originated at node \( i \in N \).

\( b_i \)  
Number of vehicles required to transport the flow destined to node \( i \in N \).

\[
O_i = \sum_{j \in N} w_{ij} \quad a_i = \left[ \frac{O_i}{u} \right]
\]

\[
D_i = \sum_{j \in N} w_{ji} \quad b_i = \left[ \frac{D_i}{u} \right]
\]
Mathematical model – Decision variables

\[ x_{ij} = \begin{cases} 
1, & \text{if node } i \in N \text{ is allocated to a hub at node } j \in H, \\
0, & \text{otherwise.}
\end{cases} \]

\( (x_{jj} = 1 \text{ indicates that a hub is established at node } j \in H. ) \)

\[ y_{jq}^m = \begin{cases} 
1, & \text{if capacity level } q \in Q \text{ is installed at hub } j \in H \text{ for transportation mode } m \in M, \\
0, & \text{otherwise.}
\end{cases} \]

\[ f_{ijk} = \quad \text{Amount of flow originated at node } k \in N \text{ and transported from hub } i \in H \text{ to hub } j \in H \text{ using vehicle of type } v \in V. \]

\[ z_{ij}^v = \quad \text{Number of vehicles of type } v \in V \text{ used to travel from hub } i \in H \text{ to hub } j \in H. \]

\[ r^v = \quad \text{Number of rented vehicles of type } v \in V. \]
Mathematical model

Minimize

\[ \sum_{i \in N} \sum_{j \in H} c_{ij} a_i x_{ij} + \sum_{i \in N} \sum_{j \in H} c_{ji} b_j x_{ij} + \sum_{i \in H} \sum_{j \in H} \sum_{v \in V} (c_{ij}^v + oc^v) z_{ij}^v + \sum_{v \in V} rc^v r^v + \sum_{j \in H} fc_j x_{jj} \]

\[ + \sum_{j \in H} \sum_{q \in Q} \sum_{m \in M} kc_{jq}^m y_{jq}^m + \sum_{i \in N} \sum_{j \in H} mhc_j O_i x_{ij} + \sum_{i \in H} \sum_{j \in H} \sum_{k \in N} \sum_{m \in M} \sum_{v \in V_m} mhc_j^m f_{ijk}^v \]

s.t.

\[ \sum_{j \in H} x_{ij} = 1 \quad \forall i \in N \quad (1) \]

\[ x_{ij} \leq x_{jj} \quad \forall i \in N, j \in H \quad (2) \]

\[ \sum_{q \in Q} y_{jq}^m \leq x_{jj} \quad \forall j \in H, m \in M \quad (3) \]
Mathematical model

\[
\sum_{j \in H, j \neq i} z_{ij}^{\nu} \leq \sum_{q \in Q} k_{q}^{\nu} y_{iq}^{m}
\quad \forall i \in H, m \in M, \nu \in V_{m}
\tag{4}
\]

\[
\sum_{i \in H, i \neq j} z_{ij}^{\nu} \leq \sum_{q \in Q} k_{q}^{\nu} y_{jq}^{m}
\quad \forall j \in H, m \in M, \nu \in V_{m}
\tag{5}
\]

\[
\sum_{j \in H, j \neq i} \sum_{v \in V} f_{ijk}^{\nu} - \sum_{j \in H, j \neq i} \sum_{v \in V} f_{jik}^{\nu} = O_{k} x_{ki} - \sum_{l \in N} w_{kl} x_{li}
\quad \forall i \in H, k \in N
\tag{6}
\]

\[
\sum_{k \in N} f_{ijk}^{\nu} \leq u^{\nu} z_{ij}^{\nu}
\quad \forall i, j \in H : i \neq j, \nu \in V
\tag{7}
\]

\[
\sum_{i \in H} \sum_{j \in H, j \neq i} z_{ij}^{\nu} \leq o^{\nu} + r^{\nu}
\quad \forall \nu \in V
\tag{8}
\]
Mathematical model

\[ f_{ijk} \geq 0 \quad \forall i, j \in H, i \neq j, k \in N, v \in V \quad (9) \]

\[ z_{ij}^v \geq 0 \quad \text{and integer} \quad \forall i, j \in H, i \neq j, v \in V \quad (10) \]

\[ r^v \geq 0 \quad \text{and integer} \quad \forall v \in V \quad (11) \]

\[ x_{ij} \in \{0,1\} \quad \forall i \in N, j \in H \quad (12) \]

\[ y_{jq}^m \in \{0,1\} \quad \forall j \in H, q \in Q, m \in M \quad (13) \]
Local Search Algorithm

- Start with an initial solution with $p$ hubs
  - A greedy starting solution algorithm

- Apply neighborhood generation
  - 6 different generation procedures

- Assign vehicles
  - 2 different greedy type algorithms with improvement steps
    (Type I and II)

- Generate neighbors and continue until the limit for the max number of solutions is reached
Heuristic

1: \( \text{Solution} = \emptyset, \text{Neighborhood} = \emptyset \)
2: Apply Initial Solution, add the initial solution to Neighborhood
3: repeat
4: Select the next neighbor, \( n \), from the set Neighborhood
5: Apply Neighborhood Generation to \( n \), add all new neighbors to Neighborhood
6: Apply Vehicle Assignment to \( n \), calculate total cost.
7: Delete \( n \) from Neighborhood and add it to Solution
8: until \( |\text{Solution}| \geq \text{max number of solutions} \)
9: Report the solution that has the minimum cost in Solution
Neighborhood

(a) Initial solution

(b) Allocate a non-hub to a different hub

(c) Exchange a hub with a non-hub

(d) Exchange allocations of two non-hubs

(e) Increase number of hubs by one

(f) Decrease number of hubs by one

(g) Delete a hub arc
Computational Analysis

- Turkish network (16 and 81 nodes)
- CAB data set (25 nodes)
Computational Analysis

- Application parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Turkish network</th>
<th>CAB data set</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>N</td>
<td>=</td>
</tr>
<tr>
<td>$Q$</td>
<td>Small, Large</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td>Ground and air transportation</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Van, truck, trailer, airplane</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Van</th>
<th>Truck</th>
<th>Trailer</th>
<th>Airplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (ton)</td>
<td>3.5</td>
<td>15</td>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td>Fuel cost (TL/km)</td>
<td>0.5</td>
<td>1</td>
<td>1.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Fuel cost /Capacity (TL/km-ton)</td>
<td>0.143</td>
<td>0.067</td>
<td>0.048</td>
<td>0.032</td>
</tr>
<tr>
<td>Economies of scale parameter, $\alpha$</td>
<td>1</td>
<td>0.467</td>
<td>0.336</td>
<td>0.224</td>
</tr>
</tbody>
</table>
Performance of the heuristic

- Eclipse Java EE IDE, Version: Juno Service Release 1
- CPLEX 12.4
- HP Z600 workstation 2 x Intel Xeon 2.40 GHz processor
  48 GB of RAM

<table>
<thead>
<tr>
<th>Capacity</th>
<th># of solutions</th>
<th>Vehicle assign.</th>
<th>$p = \sqrt{n} - 2$</th>
<th>$p = \sqrt{n}$</th>
<th>$p = \sqrt{n} + 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose</td>
<td>6,000</td>
<td>I</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td>12,000</td>
<td>I</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td>Tight</td>
<td>6,000</td>
<td>I</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td>12,000</td>
<td>I</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td>7 instances *</td>
<td>7 instances *</td>
<td>7 instances *</td>
</tr>
</tbody>
</table>

840 runs with the Turkish network

280 runs with the CAB data set
## Performance of the heuristic

### Turkish network (16 nodes)

<table>
<thead>
<tr>
<th>Fixed cost</th>
<th>Optimal solution</th>
<th>Heuristic with generating 12,000 solutions</th>
<th>Vehicle assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obj. func. value</td>
<td>p = √n - 2</td>
<td>p = √n</td>
</tr>
<tr>
<td></td>
<td>Solution time (sec)</td>
<td>Solution time (sec)</td>
<td>Gap (%)</td>
</tr>
<tr>
<td>60,000</td>
<td>562,800</td>
<td>2,636</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>70,000</td>
<td>602,800</td>
<td>4,195</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>80,000</td>
<td>642,800</td>
<td>4,189</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>90,000</td>
<td>682,800</td>
<td>3,015</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>100,000</td>
<td>721,156</td>
<td>409</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>110,000</td>
<td>743,961</td>
<td>18</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>120,000</td>
<td>763,961</td>
<td>9</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>Average</td>
<td>2,067</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II</td>
</tr>
</tbody>
</table>
### CAB data set (25 nodes)

<table>
<thead>
<tr>
<th>Fixed cost</th>
<th>Optimal Solution</th>
<th>Heuristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obj. func. value</td>
<td>Solution time (sec)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60,000</td>
<td>848,888</td>
<td>17,849</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>70,000</td>
<td>898,888</td>
<td>5,945</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>80,000</td>
<td>948,888</td>
<td>4,332</td>
</tr>
<tr>
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</tr>
<tr>
<td>90,000</td>
<td>998,888</td>
<td>4,680</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,000</td>
<td>1,048,888</td>
<td>11,354</td>
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<tr>
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<td></td>
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<tr>
<td>110,000</td>
<td>1,098,275</td>
<td>18,909</td>
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<tr>
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</tr>
<tr>
<td>120,000</td>
<td>1,138,275</td>
<td>10,362</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>10,490</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Performance of the heuristic

<table>
<thead>
<tr>
<th># of solutions</th>
<th>Vehicle assignment</th>
<th>( p = \sqrt{n} - 2 )</th>
<th>( p = \sqrt{n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,000</td>
<td>I</td>
<td>3.88</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>4.03</td>
<td>3.71</td>
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<td>24,000</td>
<td>I</td>
<td>3.87</td>
<td>2.69</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.91</td>
<td>2.19</td>
</tr>
</tbody>
</table>

- **CAB data set (25 nodes)**
- **Objective function value**
- **Solution time (sec)**
- **Vehic. Assign**
- **Solution time (sec)**
- **Gap (%)**
- **Solution time (sec)**
- **Gap (%)**
- **Average**
- **Heuristic**
- **\( p = \sqrt{n} - 2 \)**
- **\( p = \sqrt{n} \)**
Lower bound

- By relaxing the integer variables ($z_{ij}^\nu$ and $r^\nu$)

<table>
<thead>
<tr>
<th>Fixed cost</th>
<th>Optimal Solution</th>
<th>Lower bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obj. func. value</td>
<td>Solution time (sec)</td>
</tr>
<tr>
<td>60,000</td>
<td>563,052</td>
<td>1,345</td>
</tr>
<tr>
<td>70,000</td>
<td>603,052</td>
<td>1,639</td>
</tr>
<tr>
<td>80,000</td>
<td>643,052</td>
<td>906</td>
</tr>
<tr>
<td>90,000</td>
<td>683,052</td>
<td>998</td>
</tr>
<tr>
<td>100,000</td>
<td>721,656</td>
<td>347</td>
</tr>
<tr>
<td>110,000</td>
<td>744,361</td>
<td>14</td>
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<tr>
<td>120,000</td>
<td>764,361</td>
<td>15</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>752</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed cost</th>
<th>Optimal Solution</th>
<th>Lower bound</th>
</tr>
</thead>
<tbody>
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<td>9</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>2,067</td>
</tr>
</tbody>
</table>

Turkish network – Tight capacity

- LB gap with the CAB data set: 0.49%
Computational Analysis

- Sensitivity analysis with the complete Turkish network data (81 nodes)
  - Fixed costs
  - Hub capacities
  - Fleet size
  - Vehicle renting costs
- 75,000 solutions with $p = \sqrt{n} = 9$
- Average solution time: 15.2 minutes
- Average gap from the lower bound: \(~7\%\)
Computational Analysis

Node

<table>
<thead>
<tr>
<th>Node</th>
<th>Small ground hub</th>
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Conclusions

- Hub location problem from a service network design perspective
- Alternative transportation modes and different types of vehicles on the hub network
- A mixed-integer programming formulation correctly modeling economies of scale
- Hub capacities and material handling costs
- An efficient local search heuristic
- Extensive computational analysis on the CAB and Turkish network data sets
- Solved problems with the 81-node Turkish network
References – 1

References – 2

THANK YOU

Sibel Alumur Alev
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA
sibel.alumur@uwaterloo.ca

University of Missouri - St. Louis
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