Optimal Wholesale Facilities Location within the Fruit and Vegetables Supply Chain: A LP-MIP Heuristic Approach

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Outline

• Introduction and background

• Hub Location Problem

• Objective and Problem Formulation

• Experimental Results and Analysis

• Conclusions, and

• Future Work
Introduction

- Population growth is posing a challenge to food availability and accessibility.
- To maintain the balance between supply and the growing demand for the food products, the number of production and consumption sites increase.
- The emergence of more production-consumption nodes also complicates food accessibility and availability.
- Perishability and freshness challenges
- Interest in locally produced food
- “Know Your Food, Know Your Farmer” (USDA)

Question: “What is a practical way of bringing food products to customers at reasonable cost by significantly increasing the role of locally produced foods in satisfying existing demand and consumers’ need?”
The hub location problem arises when flow (travelers, airline passengers, cargos, farm products, mails, etc.) must be sent from an origin node to a destination node. A hub location is defined as existing wherever placing a direct link between each OD pair is either challenging or costly.

Campbell (1994) and Campbell and O’Kelly (1994 – 2012) provide comprehensive introduction, survey, and commentary review on hub location research. Formulations and solution approaches for the Capacitated Multiple Allocation Hub Location Problem (CMAHLP) are presented in (Ebery et al. 2000). GIS-based solutions are also proposed to solve the location problem by finding the optimal number and location of facilities in a supply-demand management network (Gu et al. 2009, Trubint et al. 2006, Large et al. 2004).
Food Distribution Hubs

- The hub network allows a large number of production and consumption nodes to be connected with fewer links.
- Reducing the number of links and their distances reduces food transportation costs and final product prices.
Based on 2007 USDA/NASS data, a total of 2,522 counties in the U.S. contain fruit- or vegetable-producing farms.
Objective

- Design and locate an optimal hub-based logistics network of wholesale markets within the food supply chain system through the followings:
  
  - Considering transportation impedance where the total travel cost between the processing and retail markets is minimized.
  - The product does not travel more than the maximum allowed predefined distance between the processing-wholesale hub and retail market (regional food access) for Land Transport.
  - Higher cost is associated with Air Transport.
  - Wholesale hubs are closer to the retail markets than to the processing facilities.
  - The optimal number of wholesale market hub locations is determined based on logistic performance, hub capacity and demand in the supply chain network.
Objective (Cont.)
Minimize

\[ TC = \sum_{i,h \in FS} ms_{ih} f(d_{ih}) + \sum_{h,j \in FD} md_{hj} f(d_{hj}) \cdot CL + \sum_{i,h \notin FS} ms_{ih} f(d_{ih}) + \sum_{h,j \notin FD} md_{hj} f(d_{hj}) \cdot CA + \sum_h F_h Z_h \]  

Subject to:

\[ \sum_h ms_{ih} \leq p_i \quad \text{for all } i \]  

\[ \sum_h md_{hj} = c_j \quad \text{for all } j \]  

\[ \sum_i ms_{ih} = \sum_j md_{hj} \quad \text{for all } h \]  

\[ \sum_i ms_{ih} \leq Z_h \cdot U_h \quad \text{for all } h \]  

\[ \sum_i ms_{ih} \geq Z_h \cdot L_h \quad \text{for all } h \]  

\[ \sum_j md_{hj} \leq Z_h \cdot U_h \quad \text{for all } h \]  

\[ \sum_j md_{hj} \geq Z_h \cdot L_h \quad \text{for all } h \]  

Where

\[ Z_h = \begin{cases} 1 & \text{if county node } h \text{ is a hub} \\ 0 & \text{therewise} \end{cases} \]

\[ ms_{ih}, md_{ih} \geq 0 \]
## Variable Definition

<table>
<thead>
<tr>
<th>Index (variable)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>production location</td>
</tr>
<tr>
<td>$j$</td>
<td>consumption location</td>
</tr>
<tr>
<td>$h$</td>
<td>hub location</td>
</tr>
<tr>
<td>$f(d_{ij})$</td>
<td>impedance values as function of highway miles between any $i - j$ location pairs</td>
</tr>
<tr>
<td>$CL$</td>
<td>fixed cost (Land Transportation) per mile per ton value ($ per ton mile)</td>
</tr>
<tr>
<td>$CA$</td>
<td>fixed cost (Air Transportation) per mile per ton value ($ per ton mile)</td>
</tr>
<tr>
<td>$F_h$</td>
<td>fixed cost of locating and operating a hub in county $h$ ($)</td>
</tr>
<tr>
<td>$N$</td>
<td>a set of counties to be interconnected</td>
</tr>
<tr>
<td>$H$</td>
<td>the estimated set of total hubs to be constructed</td>
</tr>
<tr>
<td>$p_i$</td>
<td>total supply in production location $i$ (tons)</td>
</tr>
<tr>
<td>$c_j$</td>
<td>total demand in consumption location $j$ (tons)</td>
</tr>
<tr>
<td>$ms_{ih}$</td>
<td>fraction of the quantities shipped from production location $i$ to hub location $h$ (tons)</td>
</tr>
<tr>
<td>$md_{hj}$</td>
<td>fraction of the quantities shipped from hub location $h$ to consumption location $j$ (tons)</td>
</tr>
<tr>
<td>$Z_h$</td>
<td>integer variable: $Z_h = 1$ if location $h$ is a hub, and 0 otherwise</td>
</tr>
<tr>
<td>$U_h$</td>
<td>maximum capacity of hub facility in location $h$ (tons)</td>
</tr>
<tr>
<td>$L_h$</td>
<td>minimum capacity of hub facility in location $h$ should fulfilled (tons)</td>
</tr>
<tr>
<td>$TC$</td>
<td>total cost ($)</td>
</tr>
<tr>
<td>$TP$</td>
<td>threshold distance between production locations and hub locations (mile)</td>
</tr>
<tr>
<td>$TM$</td>
<td>threshold distance between hub locations to consumption locations (mile)</td>
</tr>
<tr>
<td>$FS$</td>
<td>subsets of distances between production regions to hub locations with respect to $TP$</td>
</tr>
<tr>
<td>$FD$</td>
<td>subsets of distances between hub locations to consumption locations with respect to $TM$</td>
</tr>
</tbody>
</table>
Goal:
To understand how optimal locations of the Wholesale Markets adjust over time with changing hub capacity constraints and products’ travel distance.
The network consists a total of **3080** counties

Maximum **distance** of **3,637.3** miles is between Monroe, Florida and San Juan, Washington

Maximum production is estimated to be **6,648,867** tons in Fresno County in the state of California (1,682,763 (tons) fruit and 4,966,104 (tons) vegetable).

Maximum demand is estimated to be **1,487,885** tons in Los Angeles County in the state of California.

Total Fruit + Vegetable **production** is **75,454,796** tons

Demand in each county is estimated by multiplying US per capita consumption of fruits and vegetables by county population

Total **demand** for Fruit + Vegetable is **45,409,579** tons
A heuristic approach is developed to considerably reduce the computational time:

- Initially relax the integer variables \((0 \leq Z_h \leq 1)\) of model solve a relaxed MILP (RMILP) as a linear programming problem.
- The solution to this model would potentially contain some excluded nodes with \(Z_h = 0\) and some potential hubs with \(Z_h \neq 0\).
- Omit those hub candidates from the model and build a smaller sized model called Intermediate Model (IM).

Naturally, the IM model eliminates \(Z_h, ms_{ih}, md_{hj}\) variables and all associated constraints related to \(Z_h = 0\).
We implemented our model and algorithm in GAMS 23.7.3 and used CPLEX 12.4 as the MILP solver with the following CPLEX options:
solvefinal=0;  threads=4;

All optimization studies were carried out on High Performance Computing (HPC) Systems, each case running on four processor cores with a memory allocation of 60 GB. Several simulations were conducted using the model to determine the optimal number of U.S. F&V hubs and their locations.
Experimental Results and Analysis (Cont.)

Result of number of hubs with *unlimited average travel distance and limited upper/lower bound of hub capacity
*distance greater than the maximum distance between the two farthest counties across the U.S., **unlimited = 500,000

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Hub(s) Max Capacity (Ton/100)</th>
<th>Hub(s) Min Capacity (Ton/100)</th>
<th>No. of Hub(s)</th>
<th>No. of Supply Nodes Used only LandTr</th>
<th>Objective Function x10^6</th>
<th>Relative GAP</th>
<th>Elapsed Time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td><strong>unlimited</strong></td>
<td>500</td>
<td>92</td>
<td>2411</td>
<td>729</td>
<td>0.029</td>
<td>8:20</td>
</tr>
<tr>
<td>B</td>
<td>50,000</td>
<td>500</td>
<td>91</td>
<td>2411</td>
<td>729</td>
<td>0.029</td>
<td>9:26</td>
</tr>
<tr>
<td>C</td>
<td>50,000</td>
<td>1</td>
<td>86</td>
<td>2411</td>
<td>730</td>
<td>0.029</td>
<td>13:45</td>
</tr>
</tbody>
</table>

Min = ?
Max = ?
*ATD = Unlimited

Cases A/ B/ C

Case B: UC = 50,000, LC = 500

Case C: UC = 50,000, LC = 1

DDM: Demand nodes supported with land & AirTr
DOA: Demand nodes supported with only AirTr
DOL: Demand nodes supported with only LandTr

SDM: Supply Nodes Used Land & AirTr
SOA: Supply Nodes Used only AirTr
SOL: Supply Nodes Used only LandTr

*ATD = Average Travel Distance, UC = Upper hub capacity limit, LC = Lower hub capacity limit
Experimental Results and Analysis (Cont.)

### Result of number of hubs with fixed average travel distance and variable upper bound of hub capacity

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Hub(s) Max Capacity (Ton/100)</th>
<th>No. of Hub(s)</th>
<th>No. of Supply Nodes Used only LandTr</th>
<th>No. of Supply Nodes Used only AirTr</th>
<th>No. of Supply Nodes Used Land&amp; AirTr</th>
<th>No. of Demand nodes supported with only LandTr</th>
<th>No. of Demand nodes supported with only AirTr</th>
<th>No. of Demand nodes supported with land &amp; AirTr</th>
<th>Objective Function x10^6</th>
<th>Relative GAP</th>
<th>Elapsed time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>10,000</td>
<td>160</td>
<td>2418</td>
<td>17</td>
<td>2</td>
<td>1634</td>
<td>1422</td>
<td>24</td>
<td>14,451</td>
<td>0.024</td>
<td>2:30</td>
</tr>
<tr>
<td>E</td>
<td>5,000</td>
<td>170</td>
<td>2429</td>
<td>4</td>
<td>1</td>
<td>1645</td>
<td>1407</td>
<td>28</td>
<td>14,650</td>
<td>0.025</td>
<td>5:01</td>
</tr>
<tr>
<td>F</td>
<td>2,000</td>
<td>258</td>
<td>2435</td>
<td>3</td>
<td>1</td>
<td>1577</td>
<td>1405</td>
<td>28</td>
<td>15,757</td>
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</tr>
</tbody>
</table>

Min = 1,000  
Max = ?

Minimizing the objective function by varying the upper bound of hub capacity.
Dual Transportation Supply Maps

Dual Transportation Demand Maps

Case D: UC = 10,000
Case E: UC = 5,000
Case F: UC = 2,000

ATD_SH = Average Travel Distance from supply locations to hubs, ATD_HD = Average Travel Distance from hubs to demand locations, UC = Upper hub capacity limit, LC = Lower hub capacity limit
## Experimental Results and Analysis (Cont.)

### Result of number of hubs with variable average travel distance and lower bound of hub capacity

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Production-Hub Max Dist (Mile)</th>
<th>Hub(s) Min Capacity fulfilled (Ton/100)</th>
<th>No. of Hub</th>
<th>No. of Supply Nodes Used only LandTr</th>
<th>No. of Supply Nodes Used only AirTr</th>
<th>No. of Demand nodes supported with only LandTr</th>
<th>No. of Demand nodes supported with only AirTr</th>
<th>No. of Demand nodes supported with land &amp; AirTr</th>
<th>Objective Function x10^6</th>
<th>Relative GAP</th>
<th>Elapsed Time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>500</td>
<td>1,000</td>
<td>160</td>
<td>2418</td>
<td>17</td>
<td>2</td>
<td>1634</td>
<td>1422</td>
<td>24</td>
<td>14,451</td>
<td>0.024</td>
</tr>
<tr>
<td>H</td>
<td>500</td>
<td>500</td>
<td>193</td>
<td>2424</td>
<td>10</td>
<td>1</td>
<td>1743</td>
<td>1302</td>
<td>35</td>
<td>14,286</td>
<td>0.012</td>
</tr>
<tr>
<td>I</td>
<td>500</td>
<td>1</td>
<td>288</td>
<td>2438</td>
<td>0</td>
<td>0</td>
<td>1860</td>
<td>1162</td>
<td>58</td>
<td>14,151</td>
<td>0.003</td>
</tr>
<tr>
<td>J</td>
<td>200</td>
<td>1,000</td>
<td>202</td>
<td>2142</td>
<td>276</td>
<td>16</td>
<td>1846</td>
<td>1200</td>
<td>34</td>
<td>27,779</td>
<td>0.018</td>
</tr>
<tr>
<td>K</td>
<td>200</td>
<td>500</td>
<td>280</td>
<td>2307</td>
<td>111</td>
<td>15</td>
<td>2179</td>
<td>843</td>
<td>58</td>
<td>27,513</td>
<td>0.009</td>
</tr>
<tr>
<td>L</td>
<td>200</td>
<td>1</td>
<td>514</td>
<td>2382</td>
<td>36</td>
<td>20</td>
<td>2415</td>
<td>616</td>
<td>49</td>
<td>27,340</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Min = ?
Max = 10,000

\[ ? \text{ miles} \quad 200 \text{ mile} \]

Min = ?
Max = 10,000
**UC = 10,000**

**Case H:** *ATD_SH = 500, ATD_HD = 200, LC = 500

**Case K:** *ATD_SH = 200, ATD_HD = 200, LC = 500

*ATD_SH = Average Travel Distance from supply locations to hubs, ATD_HD = Average Travel Distance from hubs to demand locations, UC = Upper hub capacity limit, LC = Lower hub capacity limit*
## Experimental Results and Analysis (Cont.)

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Hub(s) Min Capacity fulfilled (Ton/100)</th>
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<th>No. of Demand nodes supported with only LandTr</th>
<th>No. of Demand nodes supported with only AirTr</th>
<th>No. of Demand nodes supported with Land &amp; AirTr</th>
<th>Objective Function x10^6</th>
<th>Relative GAP</th>
<th>Elapsed Time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*I'</td>
<td>500</td>
<td>283</td>
<td>2436</td>
<td>2</td>
<td>0</td>
<td>1863</td>
<td>1163</td>
<td>54</td>
<td>1,4151</td>
<td>0.000</td>
<td>56:01</td>
</tr>
<tr>
<td>**I</td>
<td>500</td>
<td>288</td>
<td>2438</td>
<td>0</td>
<td>0</td>
<td>1860</td>
<td>1162</td>
<td>58</td>
<td>14,151</td>
<td>0.003</td>
<td>1:47</td>
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<tr>
<td>G'</td>
<td>1,000</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.024</td>
<td>72:00</td>
</tr>
<tr>
<td>G</td>
<td>1,000</td>
<td>160</td>
<td>2418</td>
<td>17</td>
<td>2</td>
<td>1634</td>
<td>1422</td>
<td>24</td>
<td>14,451</td>
<td>0.024</td>
<td>2:30</td>
</tr>
</tbody>
</table>

**Result comparison of the MIP and LP-MIP solutions**

* (') Conventional MIP solution (CPLEX)

**LP-MIP Solution

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**Experimental Results and Analysis (Cont.)**

- **Min = 1**
- **Max = 10,000**

**Diagram 1:**
- 500 miles
- Green node: P
- Blue node: H
- Red node: C

**Diagram 2:**
- 500 miles
- Green node: P
- Blue node: H
- Red node: C
a) Land and air transport connections of supply-to-hub nodes
b) Land and air transport connections of hub-to-demand nodes

Min = 1,000
Max = 2,000

500 miles

200 miles
Maximum supply connection links the hub 39109 and maximum hub 30093 to demand connection
• This work presents a mathematical formulation of the food industry hub location problem and a LP-MIP heurist solution.

• Our findings allow us to draw several implications for supporting regional food systems by locating wholesale facilities to enable access to production and consumption sites.

• The model is sensitive to the distance over which commodities are allowed to travel (Land and Air Transport)

• The results show the effect of varying these parameters on the selection of hub locations.

• Our analysis is potentially useful for policymakers and private decision-makers from a number of perspectives. (social planner - private sector firms)
Future Work (Limitations)

- **Products are assumed to be undifferentiated**
  - Leads to unrealistic commodity mix outcomes

- **Cost to build hubs and ship products are not empirically estimated**
  - These costs drive model results so such data points should be empirically estimated and/or validated with market data

- **Consumer preferences are not represented**
  - Limits the models use for policy scenario analysis

- **Model does not distinguish shipping verses handling costs**
  - Transportation hubs do not exist
  - Scale economies in transportation are assumed away

- **Import and Export has not been considered**
Future Work (Integrated Modeling Approach)

- Restate the mixed integer hub location model as a model of optimal investment
  - Hub construction and operation costs are empirically estimated
  - Economies of scale are empirically estimated

- Restate the model of intra-industry trade to include hub operations with economies of scale estimated in optimal investment model
  - The role of distribution infrastructure in determining marketability of regionally sourced produce is represented in the model
  - The two combined models complete the node-hub, hub-hub, and hub-note process
Future Work (Research Questions to be Addressed)

- What are the costs and impact of new hub infrastructure investments in the U.S.?
  - Where and how many hubs are optimal
  - How much of a gain in market share can regionally sourced produce achieve through a more cost competitive distribution network

- What role do farmland and labor supply constraints play in answers to above question?

- What impact do produce costs and availability occur with large energy price spikes?
  - Baseline impacts versus post hub investment impacts
Future Work (Cont.)

Supply $p$

Production Hub $s$

GMA Hub $r$

Demand $d$

Import Hub $i$

Export Hub $e$
THANK YOU