OPTIMIZATION AND DESIGN OF ROBUST SUPPLY CHAIN NETWORKS

A Thesis Presented

By

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ABSTRACT

A robust and cost effective distribution network is critical to any fast growing company, both to meet demand under normal conditions and to adapt to temporary facility distributions. This paper develops two mixed integer programming models to optimize the supply chain of a national medical consumable supplies company with international manufacturers or otherwise geographically remote from demand locations and consistent monthly repeating demand and to provide some robustness against temporary disruption of facility operations. Specifically, $p$-median single-echelon and hub-and-spoke multi-echelon models are used to determine optimal locations of warehouses and distribution facilities that minimize total transportation cost, with a potential savings in the motivating application of 13% (approximately $1.4 million annually). Sensitivity analyses to a range of scenarios, furthermore, suggest that the optimal distribution network is affected primarily by manufacturer locations rather than customer locations within United States.
ACKNOWLEDGEMENT

I would like to express the deepest appreciation to my advisor and committee chair, Dr. James C. Benneyan, who supported me throughout my thesis. Thanks to him, I have been able to work on projects related to supply chain and optimization. Working with an industry partner, NxStage Medical Inc., has given me a wider exposure in the field of supply chain.

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I would like to thank all my loved ones, who have supported me throughout entire process, both by keeping me harmonious and helping me to shape my today and tomorrow. This thesis is a dedicated to my parents who have presented me the opportunity of an education from the best institutions and help throughout my life. This thesis would not happen to be possible without my parents Mr. Ramanathan Radha Krishnan and Ms. Shanthi Radha Krishnan, my brother and sister-in-law Mr. Ram Siddarth Radha Krishnan and Ms. Meena Chockalingam. I will be grateful forever for your affection.
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1. Introduction

A supply chain that ensures timely delivery is essential to almost all markets, often additionally challenging when involving inbound shipments from international or geographically remote manufacturers (Lee & Wilhelm, 2010). Given the complexity of such problems, mathematical models often are used to analyze and optimize the locations of manufacturing sites, warehouses, and distribution centers relative to demand (e.g. Baumol and Wolfe, 1958; Melkote and Daskin, 2001; Nagurney, 2010; SteadieSeifi et al., 2014). We focus here on multi-mode distribution network for consumable supplies involving transportation via trucks shipments and couriers and characterized by international or geographically remote manufacturers and repeating monthly customer demand. Products considered in the problem require constant flow of through the system due to shelf-life period and require constant replenishment of the wellbeing of the consumer. Other examples can include monthly home dialysis fluid, pharmaceutical supplies, home and cosmetic items, printed materials, and others. As an illustrating case study, we apply these models to a medical supply company with international manufacturers and compare results under a variety of conditions.

The general aim in such warehouse location problems is to locate one or more warehouses that distribute products to a set of demand locations (Campbell, 1994; Marianov, Serra, & ReVelle, 1999; O’Kelly, 1987) and facility location problems have been investigated in various contexts for decades. Starting with Weber’s 1909 work to locate a single warehouse to minimize total distance to several customers (Weber & Friedrich, 1929), while early studies often applied a min-max approach to distances between supply and demand points (Dearing & Francis, 1974) with more contemporary
studies focus on minimizing total transportation cost. There are essentially five components in facility location problems: (1) location of suppliers, (2) location of customers, (3) number of facilities being located, (4) candidate locations for facilities, and (5) performance metrics to compare alternatives (ReVelle & Eiselt, 2005). Cost is the most common criteria (Beamon, 1998) but others include the number of stages, customer responsiveness and or backorders, and inventory levels or ordering size. While much of the literature focuses on optimizing outbound shipments, inbound shipments often also can have significant impact on warehouse locations. We thus develop two types of multi-modal network models, $p$-median single-echelon problem that minimizes a weighted total distance from $p$ warehouses to end-customer demand nodes (Hakimi, 1964), and a hub-and-spoke multi-echelon model that additionally optimizes the location of distribution facilities within these networks (Campbell, 1994; Cheong, Bhatnagar, & Graves, 2007; A J Goldman, 1969; Marianov et al., 1999; Skorin-Kapov, Skorin-Kapov, & O’Kelly, 1996) respectively. Both types of problems can be difficult to solve given their complexity being of order $O(n^3)$ (A. J. Goldman, 1971; O’Kelly, Bryan, Skorin-Kapov, & Skorin-Kapov, 1996) and thus NP-hard (Kariv & Hakimi, 1979).

The remainder of this work is organized as follows. Section 2 describes the topology and assumptions of the type of medical supplies distribution network studied in this work. Section 3 describes the two network models developed for this problem and Section 4 summarizes their results. Section 5 summarizes several sensitivity analyses. Section 6 discusses general conclusions, insights, and recommendations.
2. General Context and Case Study

The structure of the current supply chain is illustrated in Figure 1, a \( l \)-median network with three basic levels: supplier locations, warehouse location, and demand locations. Products are manufactured at two international locations and sent to a U.S. warehouse from which they are distributed to customer home locations. While monthly demand for each product is known and fairly constant, delivery time windows are narrow and thus can produce high transportation costs. Products are shipped via truck from the warehouse to several courier locations that are close to the customers, and couriers then deliver the products from these secondary facilities to patients.

![Current supply chain network](image)

**Figure 1:** Current supply chain network

Demand for these is fairly stable. Due to time-sensitive demand, emergency deliveries periodically are shipped directly from the warehouse to an end-consumer. Figure 2
illustrates two alternate network structures we investigated for this supply chain, a p-
median facility location model (Bozkaya, Zhang, & Erkut, 2002; Pierre Hansen &
Mladenović, 1997) and a hub-and-spoke model (Campbell, 1994; Cheong et al., 2007;
Marianov et al., 1999; Skorin-Kapov et al., 1996). In the other applications, two
warehouses tend to be more cost efficient than single warehouse systems, whereas more
than two warehouses tends to be less efficient (Fotheringham & O’Kelly, 1989).
Figure 2: Alternative network structures: (a) p-warehouse single-echelon model, (b) hub-and-spoke multi-echelon model
Our objective in both models is to determine the optimal number and location of facilities that minimize total transportation cost. Since operational and storage costs are minimal compared to transportation cost, they are not considered in either model for the sake of simplicity. To consolidate inbound shipments from manufacturers, only full truck load (FTL) shipments are used, whereas multiple outbound modes (FTL, less than truck load (LTL), and courier) are used to distribution facilities, couriers, and customers depending on volume and required service level. Shipments exceeding 15,000 pounds can be shipped only via FTL but cannot exceed truck capacity of 44,000 pounds per truck.

Figure 3 summarizes current supplier locations, customer locations, and potential alternative warehouses and distribution facility locations. Customer demand at each location is primarily deterministic, requiring consistent amounts of consumable supplies monthly. Product currently is supplied to 151 courier locations and then delivered to end-customers. For direct shipments to patients, 380 locations can be served via LTL and 1699 locations can be served via courier. Emergency shipments are satisfied directly from the facility using courier service providers. Twenty-six additional candidate warehouse distribution facility locations (13 of each) were considered in the models.
Figure 3: Candidate locations considered in the analysis
3. Mathematical Models

3.1. P-warehouse single-echelon model

Given a set of candidate warehouse locations $J$, the binary decision variable $x_j = 1$ denotes if location $j$ is chosen and 0 otherwise. Warehouses can provide shipments of any product $l \in L$, with $f_{jkl}$ denoting outbound shipment quantities of product $l$ from warehouse $j$ to demand location $k$ and $\tilde{f}_{ijkl}$ denoting inbound quantities to warehouse $j$ from supplier $i$ for product $l$. FTL trucking costs for inbound and outbound shipments, $c_{ij}$ and $c_{jk}^1$ respectively, are based on distance, while the LTL cost $c_{jk}^2$ is based on shipment weight. Cost of shipments via courier service providers is denoted by $c_{jk}^3$, with the binary variable $y_{jk} = 1$ if warehouse $j$ supplies courier location $k$. The decision variables $\bar{t}_{ij}$ and $t_{jk}^1$ indicate the number of monthly FTL trucks from manufacturer $i$ to warehouse $j$ and from warehouse $j$ to demand location $k$, respectively. The decision variable $t_{jk}^2$ indicates the weight of an LTL shipment from warehouse $j$ to demand location $k$. 
Table 1: Notation for parameters and decision variables used in both models

<table>
<thead>
<tr>
<th>Index Sets:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$</td>
<td>Index set of manufacturers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J$</td>
<td>Index set of candidate warehouse locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>Index set of demand locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>Index set of products</td>
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<table>
<thead>
<tr>
<th>Parameters:</th>
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<tbody>
<tr>
<td>$n$</td>
<td>Number of operating warehouses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{kl}$</td>
<td>Required quantity at demand location $k$ for product $l$ (in lbs.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{d}_{ij}$</td>
<td>Distance between manufacturer location $i$ and warehouse location $j$ (in miles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{jk}$</td>
<td>Distance between warehouse location $j$ and demand location $k$ (in miles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{c}_{ij}$</td>
<td>FTL cost per truck from manufacturer $i$ to warehouse $j$ (in $$/mile)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_{jk}^1$</td>
<td>FTL cost per truck from warehouse location $j$ to demand location $k$ (in $$/mile)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_{jk}^2$</td>
<td>LTL cost for flow from warehouse location $j$ to demand location $k$ (in $$/lbs.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_{jk}^3$</td>
<td>Cost of courier shipment from warehouse location $j$ to demand location $k$ (in $)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_{il} = \begin{cases} 1 &amp; \text{if manufacturer } i \text{ produces product } l \ 0 &amp; \text{otherwise} \end{cases}$</td>
<td></td>
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</table>

<table>
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<tr>
<th>Decision Variables:</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\bar{f}_{ijl}$</td>
<td>Quantity of product $l$ from manufacturer $i$ to warehouse $j$ (in lbs.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{jkl}$</td>
<td>Quantity of product $l$ from warehouse $j$ to demand location $k$ (in lbs.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{t}_{ij}$</td>
<td>Number of FTL trucks from manufacturer $i$ to warehouse location $j$ (in trucks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{jk}^1$</td>
<td>Number of FTL trucks from warehouse location $j$ to demand location $k$ (in trucks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{jk}^2$</td>
<td>Weight of LTL from warehouse location $j$ to demand location $k$ (in lbs.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_j = \begin{cases} 1 &amp; \text{if there is an operating warehouse at location } j \ 0 &amp; \text{otherwise} \end{cases}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$y_{jk} = \begin{cases} 1 &amp; \text{if the operating warehouse at location } j \text{ serves demand location } k \ 0 &amp; \text{otherwise} \end{cases}$</td>
<td></td>
<td></td>
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</tbody>
</table>
Using the above notations, the $p$-median single-echelon model is:

$$
\min \left( \sum_{j \in J} \sum_{j \in J} (c_{ij} \cdot d_{ij} \cdot \bar{e}_{ij}) + \sum_{j \in J} \sum_{K \in K} (c_{jk}^1 \cdot d_{jk} \cdot t_{jk}^1) + \sum_{j \in J} \sum_{K \in K} (c_{jk}^2 \cdot t_{jk}^2) + \sum_{j \in J} \sum_{K \in K} (c_{jk}^3 \cdot y_{jk}) \right)
$$

(1.1)

s.t.

$$
\sum_{j \in J} x_j = n \quad (1.2)
$$

$$
\sum_{K \in K} (y_{jk}) \geq x_j \quad \forall j
$$

(1.3)

$$
\sum_{K \in K} (y_{jk}) \leq x_j \cdot |K| \quad \forall j
$$

(1.4)

$$
y_{jk} \leq x_j \quad \forall j, \forall k
$$

(1.5)

$$
\sum_{j \in J} y_{jk} \leq 1 \quad \forall k
$$

(1.6)

$$
\sum_{j \in J} f_{jkl} \geq r_{kl} \quad \forall j, \forall k, \forall l
$$

(1.7)

$$
f_{jkl} \leq r_{kl} \cdot y_{jk} \quad \forall j, \forall k, \forall l
$$

(1.8)

$$
\bar{e}_{ijl} \leq x_j \cdot a_{il} \cdot \sum_{K \in K} r_{kl} \quad \forall i, \forall j, \forall l
$$

(1.9)

$$
\sum_{K \in K} f_{jkl} \leq \sum_{j \in J} \bar{e}_{ijl} \quad \forall j, \forall l
$$

(1.10)

$$
\sum_{j \in J} \bar{e}_{ijl} \leq \bar{e}_{ij} \cdot 44000 \quad \forall i, \forall j
$$

(1.11)

$$
\sum_{j \in J} f_{jkl} \leq t_{jk}^1 \cdot 44000 + t_{jk}^2 \quad \forall j, \forall k
$$

(1.12)

$$
t_{jk}^2 \leq 15000 \quad \forall j, \forall k
$$

(1.13)

$$
\bar{f}, f, \bar{e}, t^1, t^2 \in \mathbb{R}^+ \quad (1.14)
$$

$$
x, y \in \{0, 1\} \quad (1.15)
$$

The objective function 1.1 minimizes total inbound and outbound cost, with the first term based on FTL trucks from manufacturers to warehouses, the second term based on the number of FTL trucks from warehouses to demand locations, the third term based on the LTL shipment weight from warehouses to demand locations, and the fourth term based on courier costs from warehouses to demand locations. Constraint 1.2 specifies the number of warehouses, $n$, to be open, while constraints 1.3 and 1.4 ensure only open warehouses serve demand locations and that all open warehouses serve at least one
demand location (but no more than the total number of demand locations). Constraints 1.5 and 1.6 ensure that a route is open only if the associated warehouse is operating and that each demand location is served by at most one warehouse.

Constraints 1.7 and 1.8 ensure that the total amount of product received by a demand location satisfies demand and that the flow of products only occurs via open routes. Constraints 1.9 and 1.10 ensure that product shipped to a warehouse comes from a supplier who produces that product and that the outflow of products from a warehouse cannot exceed its inflow. Constraints 1.11 and 1.12 determine the number of inbound and outbound FTL trucks required, as well as the total weight of LTL shipments. Constraint 1.13 limits the capacity of LTL shipments. Constraint 1.12 ensures non-negativity of the flow of product, number of FTL trucks, and weight of LTL shipments and constraint 1.15 defines decision variables $x$ and $y$ to be binary.

3.2. Hub-and-spoke multi-echelon model

In addition to previous notation, $\hat{f}_{skl}$ denotes outbound shipment quantities from distribution facility $s$ to demand location $k$ of product $l$, and $\tilde{f}_{jst}$ denotes inbound shipment quantities from warehouse $j$ to distribution facility $s$ of product $l$ are represented by. The optimization model determines the optimal number of FTL trucks needed between warehouses and distribution facilities based on the overall weight shipments required. The decision variables $\hat{t}_{js}$ and $\tilde{t}_{sk}^1$ indicate the number of FTL trucks from warehouse $j$ to distribution facility $s$ and from distribution facility $s$ to demand location $k$, respectively. The decision variable $\tilde{t}_{sk}^2$ indicates the weight of LTL shipments
from distribution facility $s$ to demand location $k$. Transportation cost in each of the segments is denoted by $\bar{c}_{js}$, $\bar{c}_{jk}^1$, and $\bar{c}_{jk}^2$, respectively, and $\bar{c}_{jk}^3$ denotes the courier cost.

**Table 2:** Additional parameters notations and decision variables used in hub-and-spoke model

<table>
<thead>
<tr>
<th>Index Sets:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$ Index set of candidate distribution facility locations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$ Number of operating distribution facilities</td>
</tr>
<tr>
<td>$d_{js}$ Distance between warehouse location $j$ and distribution facility $s$ (in miles)</td>
</tr>
<tr>
<td>$d_{sk}$ Distance between distribution facility $s$ and demand locations $k$ (in miles)</td>
</tr>
<tr>
<td>$\bar{c}_{js}$ FTL cost per truck from warehouse $j$ to distribution facility $s$ (in $$/mile)</td>
</tr>
<tr>
<td>$\bar{c}_{sk}^1$ FTL cost per truck from distribution facility $s$ to demand locations $k$ (in $$/mile)</td>
</tr>
<tr>
<td>$\bar{c}_{sk}^2$ LTL cost for flow from distribution facility $s$ to demand locations $k$ (in $$/lbs.)</td>
</tr>
<tr>
<td>$\bar{c}_{sk}^3$ Cost of courier shipment from distribution facility $s$ to demand locations $k$ (in $)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision Variables:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{f}_{jst}$ Quantity of product $l$ from warehouse $j$ to distribution facility $s$ (in lbs.)</td>
</tr>
<tr>
<td>$\tilde{f}_{sklt}$ Quantity of product $l$ from distribution facility $s$ to demand location $k$ (in lbs.)</td>
</tr>
<tr>
<td>$\hat{t}_{js}$ Number of FTL trucks from warehouse location $j$ to distribution facility $s$ (in trucks)</td>
</tr>
<tr>
<td>$\tilde{t}_{sk}^{1}$ Number of FTL trucks from distribution facility $s$ to demand location $k$ (in trucks)</td>
</tr>
<tr>
<td>$\tilde{t}_{sk}^{2}$ Total weight of LTL from distribution facility $s$ to demand location $k$ (in lbs.)</td>
</tr>
</tbody>
</table>
| $\bar{x}_{s} = \begin{cases} 
 1 & \text{if there is an operating distribution facility at } s \\
 0 & \text{otherwise} 
\end{cases}$ |
| $\bar{z}_{js} = \begin{cases} 
 1 & \text{if an operating warehouse at } j \text{ serves an operating distribution facility at } s \\
 0 & \text{otherwise} 
\end{cases}$ |
| $\bar{y}_{sk}^{1} = \begin{cases} 
 1 & \text{if the operating distribution facility at } s \text{ serves demand location } k \\
 0 & \text{otherwise} 
\end{cases}$ |
The hub-and-spoke multi-echelon model then is:

\[
\text{min} \left( \sum_{i \in I} \sum_{j \in J} (c_{ij} \ast \bar{d}_{ij} \ast \bar{e}_{ij}) + \sum_{j \in J} \sum_{k \in K} (c_{jk}^1 \ast d_{jk} \ast t_{jk}^1) + \sum_{j \in J} \sum_{k \in K} (c_{jk}^2 \ast t_{jk}^2) + \sum_{j \in J} \sum_{k \in K} (c_{jk}^3 \ast \gamma_{jk}) + \sum_{j \in J} \sum_{s \in S} (\bar{c}_{js} \ast \bar{d}_{js} \ast \bar{t}_{js}) + \sum_{s \in S} \sum_{k \in K} (\bar{e}_{sk}^1 \ast \bar{d}_{sk} \ast \bar{t}_{sk}^1) + \sum_{s \in S} \sum_{k \in K} (\bar{e}_{sk}^2 \ast \bar{t}_{sk}^2) + \sum_{s \in S} \sum_{k \in K} (\bar{c}_{sk}^3 \ast \gamma_{sk}) \right)
\]

\[
(2.1)
\]

s.t.

\[
\sum_{j \in J} x_j = n
\]

(2.2)

\[
\sum_{s \in S} \bar{x}_s = m
\]

(2.3)

\[
\sum_{s \in S} \bar{z}_{js} \leq m \ast x_j
\]

\(
\forall j
\)

(2.4)

\[
x_s \leq \sum_{j \in J} \bar{z}_{js}
\]

\(
\forall s
\)

(2.5)

\[
\sum_{k \in K} (\gamma_{jk}) \geq x_j
\]

\(
\forall j
\)

(2.6)

\[
\sum_{k \in K} (\gamma_{jk}) \leq x_j \ast |K|
\]

\(
\forall j
\)

(2.7)

\[
\sum_{k \in K} \bar{\gamma}_{sk} \geq \bar{x}_s
\]

\(
\forall s
\)

(2.8)

\[
\sum_{k \in K} \bar{\gamma}_{sk} \leq \bar{x}_s \ast |K|
\]

\(
\forall s
\)

(2.9)

\[
\gamma_{jk} \leq x_j
\]

\(
\forall j, \forall k
\)

(2.10)

\[
\bar{z}_{js} \leq x_j
\]

\(
\forall j, \forall s
\)

(2.11)

\[
\bar{z}_{js} \leq \bar{x}_s
\]

\(
\forall j, \forall s
\)

(2.12)

\[
\sum_{j \in J} \bar{z}_{js} \leq \bar{x}_s
\]

\(
\forall s
\)

(2.13)

\[
\bar{\gamma}_{sk} \leq \bar{x}_s
\]

\(
\forall s, \forall k
\)

(2.14)

\[
\sum_{j \in J} \gamma_{jk} + \sum_{s \in S} \bar{\gamma}_{sk} \leq 1
\]

\(
\forall k
\)

(2.15)

\[
\sum_{j \in J} f_{jkl} + \sum_{s \in S} \bar{f}_{skl} \geq r_{kl}
\]

\(
\forall k, \forall l
\)

(2.16)

\[
f_{jkl} \leq r_{kl} \ast \gamma_{jk}
\]

\(
\forall j, \forall k, \forall l
\)

(2.17)

\[
\bar{f}_{skl} \leq r_{kl} \ast \bar{\gamma}_{sk}
\]

\(
\forall s, \forall k, \forall l
\)

(2.18)

\[
\bar{f}_{jkl} \leq x_j \ast a_{kl} \ast \sum_{k \in K} r_{kl}
\]

\(
\forall l, \forall j, \forall l
\)

(2.19)

\[
\bar{f}_{jst} \leq \bar{z}_{js} \ast \sum_{k \in K} r_{kl}
\]

\(
\forall j, \forall s, \forall l
\)

(2.20)

\[
\sum_{k \in K} f_{jkl} + \sum_{s \in S} \bar{f}_{jst} \leq \sum_{i \in I} \bar{f}_{ijl}
\]

\(
\forall j, \forall l
\)

(2.21)

\[
\sum_{k \in K} \bar{f}_{skl} \leq \sum_{j \in J} f_{jst}
\]

\(
\forall s, \forall l
\)

(2.22)

\[
\sum_{i \in I} \bar{f}_{ijl} \leq \bar{e}_{ij} \ast 44000
\]

\(
\forall i, \forall j
\)

(2.23)

\[
\sum_{l \in L} f_{jkl} \leq t_{jk}^1 \ast 44000 + t_{jk}^2
\]

\(
\forall j, \forall k
\)

(2.24)
The objective function 2.1 minimizes the total transportation cost as previously, but now including inbound and outbound costs for distribution facilities. The first four cost terms are the same as the previously, with the additional fifth term being the transportation cost between warehouses and distribution facilities, and the remaining terms being the transportation cost from distribution facilities to demand locations based on number of FTL trucks, LTL shipment weights, courier shipments, respectively. Constraints 2.2 and 2.3 define the number of warehouses and distribution facilities, while constraints 2.4 and 2.5 ensure that only open warehouses serve distribution facilities and that all distribution facilities are served by at least one warehouse.

Constraints 2.6 - 2.9 ensure that only open facilities serve demand locations and that all open facilities serve at least one demand location. Constraints 2.10 and 2.11 ensure possible routes exist only between open warehouse and distribution facilities, while constraint 2.12 allows only one warehouse to supply to each distribution facility. Constraints 2.13 and 2.14 ensure that either a warehouse or a distribution facility serve any particular demand point, constraint 2.15 ensures at most one incoming route to each demand location (either from warehouse or distribution facility), and constraint 2.16 ensures that all customer demand is satisfied. Constraints 2.17 and 2.18 ensure that product ship only across allowed routes.
As previously, constraint 2.19 ensures that shipments to warehouses only come from suppliers who produce that product and constraint 2.20 similarly ensures shipments from warehouses to distribution facilities only through open routes. Constraints 2.21 and 2.22 ensure outbound shipments from warehouses and distribution facilities do not exceed their inbound shipments. Constraint 2.23 and 2.24 compute number of inbound FTL shipments to a warehouse, outbound FTL shipments, and total LTL weight to be shipped via each route. Constraint 2.25 enforces the capacity limit on LTL shipments. Similarly, constraints 2.26-2.28 compute FTL shipments and LTL weight for distribution facilities. Constraint 2.29 ensures non-negativity of product flow to and from all warehouses and distribution facilities, number of FTL trucks, and LTL shipment weight, and constraint 2.30 defines the decision variables \(x, y, \hat{x}, \bar{y}\) and \(z\) to be binary.
4. Results

Both models were implemented in IBM ILOG CPLEX Optimization Studio Version 12.6.0.0 running on a 64-bit Windows 7 computer with Intel Core i7-4770 CPU @ 3.40GHz and 8.00 GB of RAM. FTL transportation costs are based on distances and historical pricing collected from the internet (www.truckloadrate.com). LTL transportation cost per pound is calculated from an industry standard pricing using the “CzarLite tables”, while courier costs are calculated based on route and weight shipments.

Table 3 summarizes results for the single echelon $p$-warehouse network model, with the first two warehouses located in the southwest and the next two in the southeast. A substantial savings results by increasing the number of warehouses from one to two, with less saving beyond that. These results also indicate that warehouse location depends to a greater extent on the locations of the manufacturers than of the home customers, with in this case warehouse proximity to the Mexican border being optimal (Figure 4). To improve robustness to short-term facility shutdowns, a second warehouse in California is optimal, producing roughly $74,000 savings monthly in transportation cost, with increases in operational cost offset by the reduction in size of the current warehouse in Texas.

Some customers request for products on emergency basis due to personal requirements, these products require to be shipped via courier service providers directly from the current warehouse in order to save time but significantly costing the company.
Table 3: Optimization results for p-warehouse network analysis

<table>
<thead>
<tr>
<th>Number of warehouses</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse locations</td>
<td>Texas</td>
<td>Texas &amp; California</td>
<td>Texas, California, Kentucky</td>
<td>Texas, California, Kentucky, North Carolina</td>
</tr>
<tr>
<td>Shipment cost from manufacturer to warehouse locations</td>
<td>$271,898</td>
<td>$204,184</td>
<td>$258,566</td>
<td>$276,286</td>
</tr>
<tr>
<td>Shipment cost from warehouses to demand locations</td>
<td>$321,907</td>
<td>$295,999</td>
<td>$252,262</td>
<td>$226,603</td>
</tr>
<tr>
<td>Emergency shipment cost from warehouses to demand locations</td>
<td>$300,855</td>
<td>$320,320</td>
<td>$275,408</td>
<td>$267,275</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$894,660</td>
<td>$820,503</td>
<td>$786,236</td>
<td>$770,164</td>
</tr>
<tr>
<td>Savings</td>
<td>-</td>
<td>$74,157</td>
<td>$108,424</td>
<td>$124,496</td>
</tr>
<tr>
<td>Annual savings</td>
<td>-</td>
<td>$889,884</td>
<td>$1,301,088</td>
<td>$1,493,952</td>
</tr>
<tr>
<td>% of savings</td>
<td>-</td>
<td>8.29%</td>
<td>12.12%</td>
<td>13.92%</td>
</tr>
<tr>
<td>Model run time</td>
<td>501.03 Sec</td>
<td>152.19 Sec</td>
<td>872.37 Sec</td>
<td>581.14 Sec</td>
</tr>
</tbody>
</table>
Table 4 & Table 5 summarize results for the multi-echelon model, here for practical purpose fixing the warehouse location based on model 1 (p-warehouse single-echelon) results assuming just one warehouse or multiple warehouses respectively, and then finding the optimal number and locations for distribution facilities.
Table 4: Results for multi-echelon model assuming just one warehouse

<table>
<thead>
<tr>
<th>Number of distribution facilities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse location</td>
<td>Texas</td>
<td>Texas</td>
<td>Texas</td>
<td>Texas</td>
<td>Texas</td>
</tr>
<tr>
<td>Distribution facility locations</td>
<td>-</td>
<td>North Carolina</td>
<td>Georgia, Illinois</td>
<td>Illinois, Georgia, North Carolina</td>
<td>Georgia, Illinois, North Carolina, California</td>
</tr>
<tr>
<td>Shipment cost from warehouse to demand locations</td>
<td>$321,907</td>
<td>$194,324</td>
<td>$108,930</td>
<td>$108,930</td>
<td>$58,840</td>
</tr>
<tr>
<td>Emergency shipment cost from warehouse to demand locations</td>
<td>$300,855</td>
<td>$170,097</td>
<td>$134,262</td>
<td>$134,175</td>
<td>$108,530</td>
</tr>
<tr>
<td>Shipment cost from warehouse to distribution facilities</td>
<td>-</td>
<td>$52,484</td>
<td>$67,440</td>
<td>$75,891</td>
<td>$98,248</td>
</tr>
<tr>
<td>Shipment cost from distribution facility to demand locations</td>
<td>-</td>
<td>$60,265</td>
<td>$121,652</td>
<td>$99,599</td>
<td>$120,915</td>
</tr>
<tr>
<td>Emergency shipment cost from distribution facility to demand locations</td>
<td>-</td>
<td>$95,197</td>
<td>$119,063</td>
<td>$115,144</td>
<td>$133,610</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$894,660</td>
<td>$844,265</td>
<td>$823,245</td>
<td>$805,637</td>
<td>$792,041</td>
</tr>
<tr>
<td>Savings</td>
<td>-</td>
<td>$50,395</td>
<td>$71,415</td>
<td>$89,023</td>
<td>$102,619</td>
</tr>
<tr>
<td>Annual savings</td>
<td>-</td>
<td>$604,740</td>
<td>$856,980</td>
<td>$1,068,276</td>
<td>$1,231,428</td>
</tr>
<tr>
<td>% of savings</td>
<td>-</td>
<td>5.63%</td>
<td>7.98%</td>
<td>9.95%</td>
<td>11.47%</td>
</tr>
<tr>
<td>Model run time</td>
<td>12.53 Sec</td>
<td>532.26 Sec</td>
<td>36.63 Sec</td>
<td>44.98 Sec</td>
<td>53.63 Sec</td>
</tr>
</tbody>
</table>
Table 5: Results for multi-echelon model assuming multiple warehouses

<table>
<thead>
<tr>
<th>Number of warehouses</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of distribution facilities</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Warehouse locations</td>
<td>Texas</td>
<td>Texas, California</td>
<td>Texas, California</td>
<td>Texas, California</td>
<td>Texas, California</td>
<td>Texas, California, Kentucky</td>
<td>Texas, California, Kentucky</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$894,660</td>
<td>$820,503</td>
<td>$778,010</td>
<td>$754,499</td>
<td>$739,677</td>
<td>$727,684</td>
<td>$786,236</td>
</tr>
<tr>
<td>Savings</td>
<td>-</td>
<td>$74,157</td>
<td>$116,650</td>
<td>$140,161</td>
<td>$154,983</td>
<td>$166,976</td>
<td>$108,424</td>
</tr>
<tr>
<td>Annual savings</td>
<td>-</td>
<td>$889,884</td>
<td>$1,399,800</td>
<td>$1,681,932</td>
<td>$1,859,796</td>
<td>$2,003,712</td>
<td>$1,301,088</td>
</tr>
<tr>
<td>% of savings</td>
<td>-</td>
<td>8.29%</td>
<td>13.04%</td>
<td>15.67%</td>
<td>17.32%</td>
<td>18.66%</td>
<td>12.12%</td>
</tr>
</tbody>
</table>
Figure 5: Breakdown of transportation costs by number of distribution facility (for a single-warehouse and a two-warehouse network)
Note that distribution facilities now are located more widely across the country and closer to customer home locations in the hub-and-spoke model. Specifically, opening a distribution facility in North Carolina will save $50,398 per month, a 5.63% savings, whereas adding two distribution facilities would save an additional $21,020 per month. Importantly, additional warehouses both will reduce total transportation cost and make the supply chain more robust to temporary failure of facilities. For example, adding a second warehouse for robustness also reduces costs by $74,157 per month, an 8.29% savings, whereas adding warehouse and distribution facility reduces costs by $116,650 per month, a 13% savings.
5. Sensitivity Analysis

Two types of sensitivity analyses were conducted to investigate the effect of geographical changes in demand and short-term facility shut downs due to weather events or other factors. In the first case, the current demand pattern has 51% of customers located in the eastern U.S., 27% in the western region, and 22% in the central and mountain regions. As a somewhat extreme-case analysis, Table 6, Table 7, Table 8 and Figure 6 summarizes optimization results if instead all demand were shifted entirely to the eastern or western or to the middle of the country. Interestingly, for all single and multi-echelon models, the optimal location of the first warehouse is unchanged in all scenarios, with subsequent warehouses concentrating closer to customer demand in the respective region and with cost savings from additional warehouses or distribution facilities significantly increasing as the demand shifts to the west coast.
### Table 6: Single-echelon network results under changes in demand

<table>
<thead>
<tr>
<th>Number of warehouses</th>
<th>Demand evenly spread on the east coast</th>
<th>Demand evenly spread on the west coast</th>
<th>Demand evenly spread in the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Warehouse location</td>
<td>Texas</td>
<td>Texas, Kentucky</td>
<td>Texas, Kentucky, North Carolina,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Georgia</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$874,560</td>
<td>$832,230</td>
<td>$812,169</td>
</tr>
<tr>
<td></td>
<td>$800,663</td>
<td>$926,568</td>
<td>$592,351</td>
</tr>
<tr>
<td></td>
<td>$573,400</td>
<td>$565,524</td>
<td>$681,213</td>
</tr>
<tr>
<td></td>
<td>$661,331</td>
<td>$652,921</td>
<td>$649,875</td>
</tr>
<tr>
<td>Model run time</td>
<td>12.37 Sec</td>
<td>545.04 Sec</td>
<td>72.322 Sec</td>
</tr>
<tr>
<td></td>
<td>612.772 Sec</td>
<td>45.942 Sec</td>
<td>99.013 Sec</td>
</tr>
<tr>
<td></td>
<td>12.45 Sec</td>
<td>427.82 Sec</td>
<td>198.48 Sec</td>
</tr>
<tr>
<td></td>
<td>614.52 Sec</td>
<td>614.52 Sec</td>
<td></td>
</tr>
</tbody>
</table>
### Table 7: One-warehouse multi-echelon network results under changes in demand

<table>
<thead>
<tr>
<th>Warehouse location</th>
<th>Demand evenly spread on the east coast</th>
<th>Demand evenly spread on the west coast</th>
<th>Demand evenly spread in the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Texas</td>
<td>Texas</td>
<td>Texas</td>
</tr>
<tr>
<td>Number of distribution facilities</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>Distribution facility location</td>
<td>- North Carolina, Ohio, North Carolina</td>
<td>Georgia, Ohio, North Carolina, Pennsylvania</td>
<td>Southern California, Northern California, Washington</td>
</tr>
<tr>
<td>Model run time</td>
<td>12.43 Sec 569.75 Sec 28.66 Sec 55.55 Sec 49.37 Sec</td>
<td>12.26 Sec 36.07 Sec 24.07 Sec 43.32 Sec 41.70 Sec</td>
<td>15.10 Sec 110.43 Sec 23.45 Sec 23.51 Sec 25.07 Sec</td>
</tr>
</tbody>
</table>

### Table 8: Two-warehouse multi-echelon network results under changes in demand

<table>
<thead>
<tr>
<th>Warehouse locations</th>
<th>Demand evenly spread on the east coast</th>
<th>Demand evenly spread on the west coast</th>
<th>Demand evenly spread in the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Texas, California</td>
<td>Texas, California</td>
<td>Texas, California</td>
</tr>
<tr>
<td>Number of distribution facilities</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>Distribution facility location</td>
<td>- North Carolina, Nevada, Pennsylvania</td>
<td>Georgia, Ohio, Nevada, Pennsylvania</td>
<td>Northern California, Washington, Utah</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$867,749 $821,181 $780,316 $760,594 $746,593</td>
<td>$592,351 $576,732 $564,828 $560,281 $558,872</td>
<td>$661,331 $640,097 $634,539 $632,783 $632,434</td>
</tr>
<tr>
<td>Model run time</td>
<td>15.83 Sec 914.59 Sec 914.85 Sec 376.48 Sec 375.57 Sec</td>
<td>15.65 Sec 615.08 Sec 283.81 Sec 614.83 Sec 374.57 Sec</td>
<td>15.88 Sec 614.78 Sec 328.40 Sec 130.60 Sec 284.86 Sec</td>
</tr>
</tbody>
</table>
Figure 6: Impact of customer location on monthly transportation cost
(a) Single-echelon (b) Single-warehouse Multi-echelon, (c) Two-warehouse Multi-echelon
Conversely, Table 9 summarizes the cost impact if the original optimal locations are used but demand changes (i.e., without re-optimization). As shown in the table, we find that the optimal locations are also optimal for the change in demand in 33% of the situations, whereas there is around 4% increase in cost if the demand shifts to the east coast, around 7% increase if the demand shifts to the west coast and 4% increase in cost if the demand is shifted to the middle of the country if the optimal network structure based on current demand in implemented.
Table 9: Change in cost for optimal network under change in demand

<table>
<thead>
<tr>
<th></th>
<th>Demand evenly spread on the east coast</th>
<th>Demand evenly spread on the west coast</th>
<th>Demand evenly spread in the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Warehouses</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of distribution facilities</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Warehouse location</td>
<td>Texas, California</td>
<td>Texas, California</td>
<td>Texas, Kentucky, California</td>
</tr>
<tr>
<td>Distribution facility location</td>
<td>North Carolina</td>
<td>North Carolina</td>
<td>Sacramento, California</td>
</tr>
<tr>
<td>Monthly transportation cost</td>
<td>$816,062</td>
<td>$811,517</td>
<td>$794,030</td>
</tr>
<tr>
<td>% increase</td>
<td>2.20%</td>
<td>4.27%</td>
<td>-</td>
</tr>
<tr>
<td>Model run time</td>
<td>15.68 Sec</td>
<td>15.80 Sec</td>
<td>110.65 Sec</td>
</tr>
<tr>
<td>Monthly transportation cost from network optimization for the demand</td>
<td>$816,062</td>
<td>$811,517</td>
<td>$794,030</td>
</tr>
<tr>
<td>% increase</td>
<td>2.20%</td>
<td>4.27%</td>
<td>-</td>
</tr>
<tr>
<td>Model run time</td>
<td>15.68 Sec</td>
<td>15.80 Sec</td>
<td>110.65 Sec</td>
</tr>
</tbody>
</table>
As a second sensitivity analysis, we analyzed transportation costs if a facility is unable to ship products for a short period of time (e.g., one month) such as due to weather, stock outs, or operational issues. We assume a ‘worse case’ scenario of one month of shutdown and that other facilities can deliver products to customers (except when only $p = 1$ warehouse). Table 10 and Table 11 indicate the change in outbound and total transportation costs for single-echelon and multi-echelon networks if one of two warehouses fails, or if one or two of three warehouses fail respectively. For comparison, the shaded columns are the previous optimal solutions when all facilities are operating.

Overall, for the three-warehouse single-echelon network, there is a savings of $108,424 per month over a one-warehouse network, or $1.3 million (12%) annually, as well as improvement in network stability. For the multi-echelon case, the two-warehouse network with one distribution facility tends to be optimal both under regular and facility failure scenarios, producing a monthly savings of $116,650 which translates to $1.4 million (13%) annually as compared to a one-warehouse network.
### Table 10: Single-echelon network facility failure analysis

<table>
<thead>
<tr>
<th>Number of warehouses</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optimal warehouse locations</strong></td>
<td>Texas</td>
<td>Texas, California</td>
<td>Texas, California, Kentucky</td>
</tr>
<tr>
<td><strong>Operating Warehouse locations</strong></td>
<td>Texas</td>
<td>California</td>
<td>Kentucky</td>
</tr>
<tr>
<td></td>
<td>California</td>
<td>Texas, California</td>
<td>Texas, Kentucky</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kentucky, California</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Texas, Kentucky, California</td>
</tr>
<tr>
<td><strong>Outbound cost</strong></td>
<td>$622,762</td>
<td>$868,699</td>
<td>$568,746</td>
</tr>
<tr>
<td></td>
<td>$533,486</td>
<td>$550,990</td>
<td>$550,990</td>
</tr>
<tr>
<td><strong>Monthly transportation Cost</strong></td>
<td>$894,660</td>
<td>$970,486</td>
<td>$855,246</td>
</tr>
<tr>
<td></td>
<td>$820,503</td>
<td>$821,157</td>
<td>$821,157</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$786,236</td>
</tr>
</tbody>
</table>

### Table 11: Multi-echelon network facility failure analysis

<table>
<thead>
<tr>
<th>Number of warehouses</th>
<th>1</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of distribution facilities</strong></td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Optimal warehouse locations</strong></td>
<td>Texas</td>
<td>Texas</td>
<td>Texas, California</td>
</tr>
<tr>
<td><strong>Optimal distribution facilities</strong></td>
<td>North Carolina</td>
<td>Georgia, Illinois</td>
<td>North Carolina</td>
</tr>
<tr>
<td><strong>Operating warehouse location</strong></td>
<td>Texas</td>
<td>Texas</td>
<td>Texas</td>
</tr>
<tr>
<td></td>
<td>Texas</td>
<td>Texas, California</td>
<td>Texas, California</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>California</td>
</tr>
<tr>
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<td>California</td>
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<td></td>
<td></td>
<td>Texas, California</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Texas, California</td>
</tr>
<tr>
<td><strong>Operating distribution facility location</strong></td>
<td>-</td>
<td>North Carolina</td>
<td>Georgia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Illinois</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Georgia, Illinois</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>North Carolina</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>North Carolina</td>
</tr>
<tr>
<td><strong>Outbound cost</strong></td>
<td>$622,762</td>
<td>$519,815</td>
<td>$483,977</td>
</tr>
<tr>
<td></td>
<td>$521,611</td>
<td>$544,505</td>
<td>$483,977</td>
</tr>
<tr>
<td></td>
<td>$483,977</td>
<td>$686,699</td>
<td>$678,745</td>
</tr>
<tr>
<td></td>
<td>$678,745</td>
<td>$619,086</td>
<td>$516,792</td>
</tr>
<tr>
<td><strong>Monthly Transportation Cost</strong></td>
<td>$894,660</td>
<td>$844,196</td>
<td>$823,308</td>
</tr>
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6. Discussion

Optimal supply chains can significantly affect transportation costs and profit margins (Melkote & Daskin, 2001). Two network structures for a medical supplies distribution network were analyzed in this work to minimize total cost and provide some protection against temporary facility shutdowns. Analyses of two potential network structures with dis-located manufacturers indicate that the manufacturers have greater influence on the distribution network structure than the locations of end-customers, with a noticeable reduction in total transportation cost if two warehouses are used. The addition of two or more distribution facilities shows marginal savings when compared to the addition of a distribution facility due to the substantial increase in transportation cost between the warehouse and distribution facilities.

In our case, the addition of one additional warehouse and one distribution facility saves approximately 13% in total transportation cost, or roughly $1.4 million annually. As more facilities are added to the supply chain the savings is higher, although operational and inventory management costs are likely to increase as well. While a complete supply chain network analysis would also include inventory cost and operational cost, we focused only on transportation cost since it comprises roughly 80% of logistics cost in this case.

We also assume there is no trans-shipment between facilities although further research could explore this (P Hansen, Peeters, & Thisse, 1983). Routes were assumed to be uncapacitated in the model considering the availability of rental trucks. Future research
therefore could incorporate truck routing and capacities. Further, inventory modeling also
could be incorporated into each alternative.
7. References


