Distribution Network Optimization in the Uniform Rental Industry

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Abstract

Optimization models are a commonly used tool to identify cost efficient network flows. Complexity increases when various products move across different paths and transportation modes within one network. To address the challenges posed by this complexity, this thesis develops a mixed integer linear programming model for a uniform rental company. The company's product families are routed through intermediary distribution centers, while others bypass these points and move directly to a regional distribution center. Various simulations were run with the objective of minimizing fixed costs, warehousing, inventory and transportation expenses. The function was constrained by flow balance, demand and capacity constraints. The optimal solution proposed a network that used less facilities than currently operated within the company, and some in new locations due to transportation cost savings. As volume increased, the network structure continued to shift further from the company's current structure. Demand increased the influence of variable rates, while transportation lane rates were a significant factor in every version of the model run.

Thesis Supervisor: Dr. Bruce Arntzen
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Dedication

This paper is dedicated to my incredibly supportive friends and family, who encouraged me to chase my dreams in pursuing an advanced degree this year. To my husband, mother, brother, and Jen – thank you for all of your love and energy. To Brittany, Sam, and Brooke, thank you for all of the laughs and distractions amidst the endless hours of work.

-Anny

To my family, friends and SCM classmates, I could not have completed this journey without you. Thank you for all of your support along the way.

-Haotian

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We would also like to thank the incredible team at our sponsor company for providing exceptional support and leadership. We are especially grateful to Kelly Blackburn, Dave Meyn, and Orlando McGee for outstanding management support and for pulling all of the internal resources necessary to develop the model.

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1. INTRODUCTION

The importance of supply chain network analysis has grown significantly over the past decade as suppliers, plants, distributors, warehouses and customers have globalized. In 2012, spending in the US logistics and transportation industry totaled $1.33 trillion, or about 8.5% of the country's gross domestic product (Schulz, 2014). As the field gains importance, executives are modernizing their supply chains to optimize supply and demand.

A global uniform supply company, hereafter referred to as The Company, has partnered with our team at MIT to examine its current supply chain operations and identify cost savings opportunities. The Company provided historical transportation data, distribution center infrastructure information, and sales figures. After examining the data, we suspected that the company could benefit from fully integrating disparate networks and streamlining operations. Therefore, the goal of our research was to develop a distribution network that optimizes the tradeoff between costs and customer service levels.

Our objective was to find the optimal distribution network layout for our sponsor company. The Company provided us with details surrounding supply and demand by product, capacity for their current DCs, and locations for expansion or new distribution centers. They also provided costs for the DCs and transportation lanes. Based on this information, we manipulated the products into groupings to simplify the complex network and built a model that would find the best way to minimize cost while still meeting demand.

1.2. Motivation

While this thesis specifically addresses The Company's distribution center network, the factors influencing the model's outcome are the same factors any company would require to optimize a similar network. The optimization model can balance distribution center fixed and variable costs with transportation costs to find the least expensive solution. The model can also tell a company how many distribution centers are needed to fulfill demand.

Section 1 provides an overview of our research question and thesis project. Section 2 provides a literature review and section 3 describes our methodology and approach. Section 4 explains the final model and its results, while section 5 discusses the outcome in further detail and provides further recommendations. Section 6 offers concluding thoughts.

2. LITERATURE REVIEW

We conducted a review of the literature related to optimization methods for supply chain networks in order to identify appropriate modeling techniques and identify constraints and parameters to include in the optimization model. After a brief overview of basic supply chain network structure in the following section, subsequent sections will review historical modeling methodologies, first observing model development (including setting objectives, variables and constraints) and then specific algorithms.

2.1. Supply Chain Network Design

A common framework for illustrating a supply chain network design consists of three stages: supplier and production stage, distribution stage and customer stage (Figure 1).

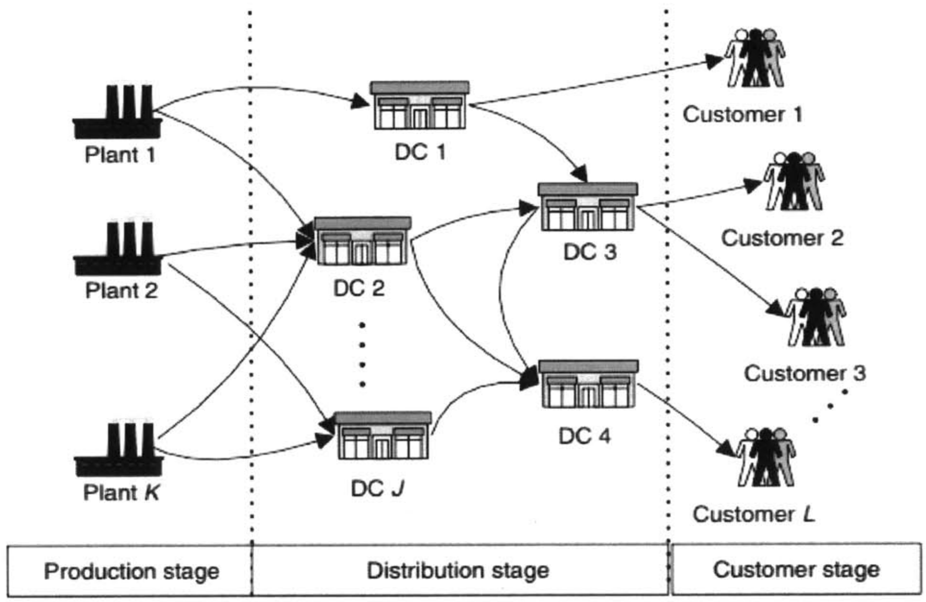


Figure 1 Multi-echelon distribution network model (Ding, Benyoucef, & Xie, 2009)

Successful companies use their supply chain design as a strategic weapon by leveraging network modeling. The objective is to determine the best location and size for their facilities while seeking to minimize the total costs associated with the production, storage, and distribution activities, along with the total investment outlays to achieve the activity levels on the various links (Nagurney, 2010).

2.2. Methods for Modeling Supply Chains

A recent technique used for analyzing supply chains is system-optimization models. Anna Nagurney (2012) proposed this framework for network design to determine optimum capacity levels and product flows for manufacturing, storing and distributing at minimal total cost. This method is unique in that it considers capacity as design variables, allowing inputs to change during simulation. The need came about as mergers and acquisitions (M&A) activity trended upward after the collapse of the economy in 2009. Therefore, this method is particularly useful for supply chain network integration in the case of M&A (Nagurney, 2010).

This method of modeling can be applied to various industries. For example, Jin, Yang, and He (2012) constructed a flow balance model while analyzing a Beijing agricultural product distribution center. The team began by building a deterministic demand model for the current system before factoring in demand variability. The goal was to minimize the sum of the fixed costs for each DC (referred to as a node), transportation costs for each lane, and penalty costs for not meeting demand. The model was constrained by flow balance restrictions and set supplier quantities. Ultimately, the researchers found that their model closely reflected the optimal scenario when applied to the Beijing agricultural business.

A different method for examining network design is the Petri net technique, which emphasizes customer order fulfillment instead of more traditional financial metrics such as minimizing total system costs. System models are built upon colored Petri nets and used to incorporate product and process concerns into the supply chain configuration process (Zhang, You, Jiao, & Helo, 2009). These models are ideal for make to order (pull systems) supply chains where efficiently delivering custom products is a necessity.

Furthermore, just in time supply chains must also be modeled in their own unique way. In order to minimize costs in such networks, researchers have incorporated fuzzy logic into bi-objective mixed integer linear programming. This model integrates procurement, production and distribution plans under fuzzy supply, production and demand by considering cross-docking and direct shipments simultaneously (Ahmadizar & Zeynivand, 2014).

Considering many of the same variables and constraints as past researchers, Aikens' (1985) research diverges through creating a model to optimize a distribution network using defined flow balance. Although his method considers many of the same variables and constraints as the others, he also factors in side constraints, such as demand volatility, that could be included in a model. His research highlights the flexibility gained by incorporating or excluding many side constraints depending on the specific nature of the system being modeled. Ultimately, as the various different models work for various individual problems, Aikens indicates that the model and algorithm can vary widely within an optimization model. Aikens also explicitly assumes unlimited capacity for the distribution centers. In practical matters, it is unrealistic to consider unlimited capacity, as this would require tremendous physical space.

Owen and Daskin (1998) counter Aikens' unlimited capacity assumption and focus heavily on the strategic importance of facility locations and related costs. The authors suggest that not enough emphasis has been placed on the lasting costs and impacts of facility placement decisions. As there are sizeable expenses involved in opening, closing, or expanding a facility, these factors must be weighted heavily in any model.

The distribution network design problem can be solved in many ways. However, in-depth analysis suggests that researchers use a particular method on a far more consistent basis than the others: mixed integer programming. While this approach has been used for decades, in recent years there has been a growing awareness of the importance of incorporating reverse and closed-loop supply chain activities along with the traditional indicators (Ozceylan & Paksoy, 2012). The scope of our research precludes incorporating closed-loop activities. However, since our thesis partner operates in the lease and rental services space, future projects analyzing detailed treatment of reverse logistics is recommended.

Although much research has already been completed on supply chain network design, there are two main gaps, which our thesis will address. Most work either optimizes cost and service levels on a strategic level, focusing on the physical structure of a network, or examines on an operational level emphasizing production planning and inventory management. Our model will reconcile the two approaches and optimize the intersection of costs and service levels. This combination of the two considerations is vital for successful implementation, as it will likely provide a more agreeable solution for different departments within the company. A decision that only benefits high level strategic planning without considering daily operational planning implications, or vice versa, is unlikely to receive full buy in from all internal parties, which is essential for success.

Lastly, restructuring a supply chain network requires making tough business decisions on opening and closing distribution centers. Department silos within organizations have led many researchers to omit working with the finance department to develop realistic costs associated with opening and closing these facilities. Our team will focus on establishing a mutual agreement between finance and operations when evaluating these financial metrics.

3. METHODOLOGY

An optimization model based on a linear program is a highly effective tool to find the optimal flow of goods through a network. (Shapiro, 2001.) Shapiro provides a detailed analysis of the spreadsheet options to optimize network flow problems using algorithms embedded in the software. While the mathematical algorithms are highly complex, the objective function can nearly always be defined as the minimum or maximum feasible result for a company's primary goal. Such goals can include cost (minimization), revenue (maximization), or transit time (minimization.) The objective function would be defined as the mathematical formula relating all the variables that contribute towards any one of these specific goals.

Microsoft Excel provides a foundation for a basic, high-level model and is often used to manage optimization models for academic and professional purposes. (Alfares, 2012; Barati, n.d.; Björk & Mezei, 2014; Shaoyun & Honglin, 2011.) However, Excel does not have the capacity to handle over 200 decision variables (Standard Excel Solver, n.d.), so the program cannot optimize large distribution networks that contain many transportation lanes. Excel offers premium purchasable add-ons for model expansion; one add-on, WhatsBest!, is an effective optimization tool with more capacity. (Shapiro, 2001.) For this reason, we used WhatsBest! to optimize The Company's sizeable distribution network.

3.1. Sponsor Company Project Development

The Company's primary goal is to analyze the cost of its current network and see whether relocating, expanding, and/or closing distribution centers would allow them to maintain the same capacity for less cost. The Company and the thesis team worked collectively to develop a simplified representation of the distribution flow to gain an understanding of how the network could be feasibly optimized. Cost drivers, including the transportation rates, distribution center fixed costs, and distribution center holding costs, were then obtained and entered into the model for optimization.

3.1.1. Sponsor company Project Scope and Parameters

Data was primarily collected from The Company's historical accounting and transportation financial records. Initial conversations to learn more about the company's network design, potential distribution center locations, and feasible shipping alternatives were held with the logistics, finance, and supply chain teams. Weekly calls supplemented these discussions to thoroughly define scope and potential restructuring of the supply chain network.

From these conversations, three divisions were determined "in-scope" for the project: First Aid & Safety, Facility Services, and Rental Garments. Though each division can ship to both the rental facilities and direct to customer, each has its own unique network. First Aid & Safety is distributed out of only one location, while Facility Services ships from two, and Rental Garments ships from eight separate distribution centers. Rental Garments also can ship through an intermediary distribution center before being shipped to its final distribution center for release to the rental facility. The Company's current distribution network is shown in Figure 2.

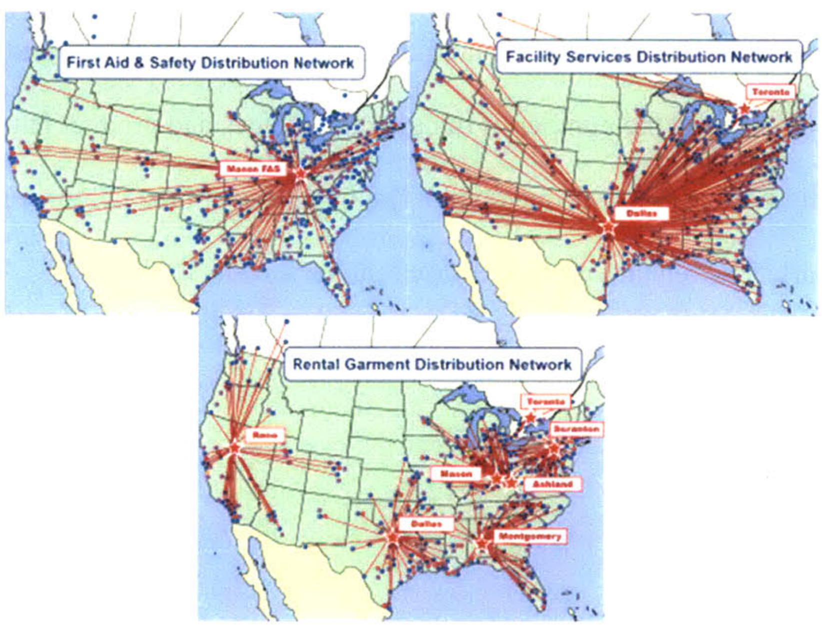


Figure 2 Distribution maps for three of The Company's product families, from distribution center to rental facilities.

Having different network arrangements introduces system complexity, making optimization of the network difficult for each product family. However, establishing multiple supply chains provides significant opportunity to enhance the network structure. For example, there is no secondary shipment location for First Aid & Safety, meaning if there were a natural disaster in Ohio, no First Aid & Safety products could be shipped. While splitting the inventory would avoid the risk associated with locating all products in one location, it would likely force the model to find a higher cost solution. Optimizing certain Rental Garments adds further complexity to the model by forcing some products through an intermediary distribution center (IDC) due to safety stock needs or supplier shipping agreements. There is no flexibility to eliminate these intermediary points, which increases system costs because additional transportation lanes are required.

To mitigate some of this complexity, we worked with The Company to group similar product types, supplier regions, and rental facility regions together. Grouping together similar nodes and variables reduced the number of transportation lanes and product families in the model. The suppliers were simply grouped into The Company's three US three ports: Miami, Seattle, and Newark. The rental region categories can be seen in Table 1.

Table 1 Rental Region Demand Groupings

Zip Code	Rental Region
40219	Central
73105	Central Plains
14086	East Central Group
M8Z1B5	Eastern Canada
32818	Florida
49534	Great Lakes
19116	Mid Atlantic Group
29605	Mid South
43219	Midwest
84104	Mountain
53718	North Central
12550	Northeast
94080	Northwest
32503	South Central
36109	Southeast
75236	Southwest
93311	Western

Finally, The Company decided to assume flat supply and demand from its historical data and to utilize historical shipment flow for the network optimization. This decision simplifies the model as it does not introduce the risk associated with forecasted regional growth but may force The Company to run a similar model in the future if there are projected shifts in regional demand.

3.1.2. Cost Drivers

Data for the costs were primarily collected from The Company's historical accounting and transportation financial records. Rates for existing lanes were pulled from The Company's freight payment system, and rates for new lanes were obtained through quotes from the current carrier base. The model did not consider mode switching, which simplified the lane rate procurement for new lanes. However, this also limited the optimization as no aggregation and consolidation cost savings opportunities could be created.

For the distribution center costs, The Company selected new potential distribution center locations to add to their current network based on internal assumptions and preferences. The Company's finance team calculated detailed costs for distribution center operations, and for opening new distribution centers and closing and expanding current distribution centers in table 2. Costs for relocating products were ignored, as The Company assumed it would burn off all inventory rather than move finished goods from one facility to another.

Table 2 Distribution Center Costs

Distribution Center Data	4	5	6	7	8	9	10
Type	DC	DC	DC	DC	DC	DC	DC
Location	Ashland	Mason	Scranton	Scranton Expansion	Dallas	Montgomery	Reno
Existing or New?	Existing	Existing	Existing	New (Expansion)	Existing	Existing	Existing
Capacity ("capacity units"/year) - Cj	2,550,000	2,390,625	478,125	318,750	3,825,000	478,125	478,125
Fixed Costs ($/per year) - DFj	$2,315,080	$1,426,176	$623,599	$311,800	$2,452,353	$644,577	$435,450
Variable Cost ($/"capacity unit") - DVj	$1.40	$1.57	$1.06	$1.06	$0.92	$1.21	$1.29
Opening Cost ($) - Doj							
Closing Cost ($) - DCj	-$2,217,816	-$1,838,848	-$997,835		-$997,835	-$997,835	-$997,835
Expansion Cost ($) - Dej				$125,000			

	11	12	13	14	15	16	17
Type	DC	DC	DC	DC	DC	DC	DC
Location	eno Expansio	Toronto	Newark	Miami	Memphis	Charlotte	Atlanta
Existing or New?	w (Expansio	Existing	New	New	New	New	New
Capacity ("capacity units"/year) - Cj	318,750	478,125	478,125	478,125	478,125	478,125	478,125
Fixed Costs ($/per year) - DFj	$217,725	$685,662	$837,973	$674,206	$479,348	$534,255	$577,942
Variable Cost ($/"capacity unit") - DVj	$1.29	$1.14	$1.50	$1.39	$1.24	$1.32	$1.34
Opening Cost ($) - Doj				$325,000	$325,000	$325,000	$325,000
Closing Cost ($) - DCj		-$997,835					
Expansion Cost ($) - Dej	$125,000						

	18	19	20	21	22	23
Type	DC	DC	DC	IDC	IDC	IDC
Location	Ontario	Seattle	Louisville	Ashland	Memphis	Miami
Existing or New?	New	New	New	Existing	New	New
Capacity ("capacity units"/year) - Cj	478,125	478,125	478,125			
Fixed Costs ($/per year) - DFj	$984,756	$836,331	$516,167			
Variable Cost ($/"capacity unit") - DVj	$1.55	$1.50	$1.29	$1.40	$1.24	$1.39
Opening Cost ($) - Doj	$325,000	$325,000	$325,000		$6,762,964	$7,653,676
Closing Cost ($) - DCj				-$997,835		
Expansion Cost ($) - Dej						

3.2. Model Development

In the network development, specific notation was used to define each node (a stock point, such as a supplier, distribution center, or rental facility) and leg (a flow, such as a Less Than Truckload or Truckload lane rate, as well as the units moving along that lane.) I represents an origin node, meaning a point from which any shipment could depart. For this reason, either the supplier or distribution center could be treated as an origin node. J, similarly, is a destination node and could be a distribution center or rental facility. K is a product family, as defined by the team in regard to unit capacity. The list of notations used for The Company's model can be found in the following Results section in Table 3 – Model Parameters.

The optimization contained formulas to force flow balance along the arcs (what goes in must come out), demand fulfillment, non-negativity, and supplier capacity limitations. A big M variable was also used to link the binary variable representing whether or not a distribution center was opening, closing, or expanding to the associated costs. Finally, the model was set to minimize the sum of the total transportation costs, distribution center costs, and handling costs.

To test our calculations before inputting The Company's data, we ran some smaller scale models. We first developed a mini model, which will be reviewed in detail in the next subsection, to reflect the supplier to distribution center to rental flow that First Aid & Safety and Facility Services utilize, as they bypass the intermediary distribution center. We created a second mini model to capture the Rental Garment flow through the intermediary distribution center. With both of these models successfully yielding optimal results, we combined them into one model that directed the Rental Garments to the intermediary distribution center and forced the First Aid & Safety and Facility Services products to bypass the intermediary distribution point.

3.3. Application of the Model

To illustrate the application of the model, the following section provides an example using simplified parameters to test the flow balance and model optimization.

Prior to inputting the specific transportation rates, costs and constraints, a mini model was run to test the network flow balance and parameters. The model contained theoretical numbers to represent demand, capacity, lane rates, and distribution center opening, closing, and expansion costs with fewer product families and excluding the intermediary distribution center.

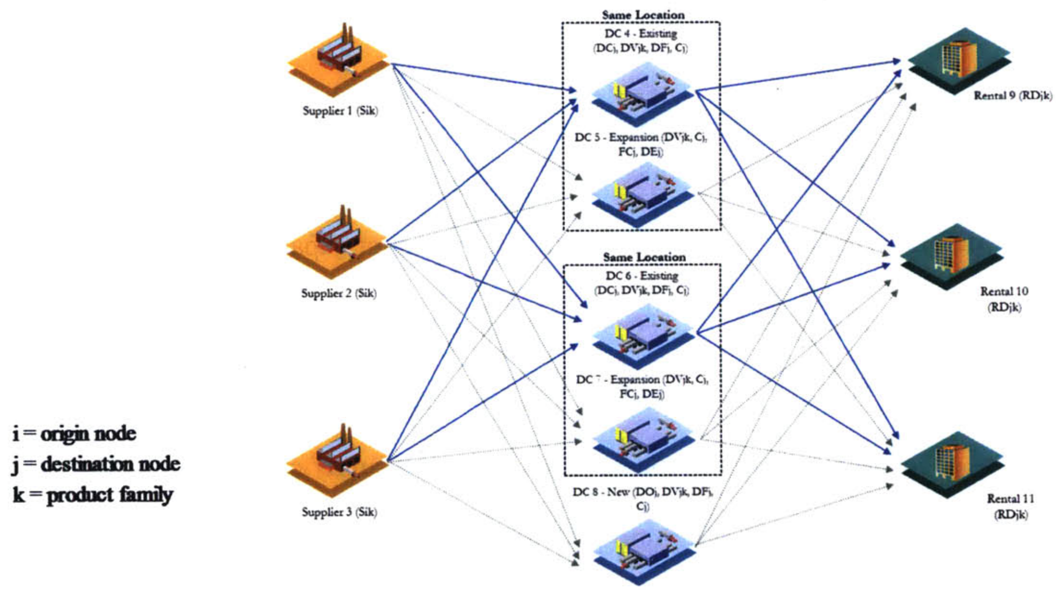


Figure 3 Mini Model (no IDC) layout

After conceptualizing the mini model, simple units were arbitrarily defined to easily comprehend the model and its results. To accurately account for handling costs across various product families, a unit of product (e.g. pair of shoes, one shirt) was standardized into a "capacity unit."

From the given data, constraints were defined. By placing a parameter that forced the number of capacity units going into each node to be the same as the number coming from each node, flow balance was enforced. Also, family product flow going into each rental facility was forced to be greater than or equal to the rental demand to ensure that demand was completely fulfilled for each product family. Non-negativity constraints were set on the distribution center and origin shipment points. Finally, the big M constraint linked the DC operation (including opening, closing, or expanding) to its relevant costs. Big M was set at $1,000,000 for this model.

Based on the constraining formulas, the mini model yielded a simple solution that recommended maintaining the two open facilities and not making any other changes. This result was expected, given the high costs of changing DC locations and the random selection of freight rates. From this mini model, a larger model can be extrapolated to include more product families, regions, intermediary DCs, and additional lane rates while still holding the same constraints.

Section 3 summarized the model development process used to answer the thesis objective of identifying a lower cost distribution network. Section 4 will address the larger model and its results. By running various models testing the effects of certain constraints, The Company can analyze aspects of its business to find ways to relax constraints and improve its optimal solution.

4. RESULTS

The mini model described in the Methodology section was built to gain understanding of how to represent and analyze The Company's supply chain network. A comprehensive binary mixed integer linear programming model, built based on the mini model, accurately represented The Company's end-to-end network design by using historical data and current network infrastructure specifications. It integrates location and capacity options for distribution centers, product family assignment and product flow. This model was used to run the simulations described in this section and to develop our recommendation. Each iteration relaxes different constraints, resulting in the three different variations for solving the problem.

4.1. Modeling Framework

All of our simulation runs solve for the same objective function with similar constraints. The simulation consisted of parameters, locations, an objective function, and constraints.

Table 3 Model Parameters

Variable	Definition	Units
i	Supplier Node	-
j	IDC Node	-
l	DC Node	-
m	Rental Region Node	-
k	Product Family	-
X_{ijk}, X_{ikl}, X_{jkl}, X_{klm}	Product Flow	Units
Sik	Supplier Capacity	Units/Year/Family
Ak	Product Family Units per Capacity Unit	Units/Capacity Unit
Bk	Pounds per Product Family Unit	Pounds
C_j , C_l	IDC, DC Capacity	"Capacity Units/Year
DF_j, DF_l	IDC, DC Fixed Costs	$/Year
DV_j, DV_l	IDC, DC Handling Cost	$/"Capacity Unit"
DO_j, DO_l	IDC, DC Opening Cost	$
DC_j, DC_l	ID, DC Closing Cost	$
DE_j, DE_l	IDC, DC Expansion Cost	$
RDmk	Rental Region Demand	Units/Year/Family
RT_{il}, RT_{lm}	TL Freight Rate	$/Pound
RL_{ij}, RL_{il}, RL_{jl}, RL_{lm}	LTL Freight Rate	$/Pound
F_j / F_l	Binary Decision Variable for IDC,DC	-
M	Large Number	-

Table 4 Model Locations

Type	Location	ID	Existing/New
Supplier Region	Miami, FL	1	Existing
Supplier Region	Seattle, WA	2	Existing
Supplier Region	Newark, NJ	3	Existing
DC	Ashland, KY	4	Existing
DC	Mason, OH	5	Existing
DC	Scranton, PA	6	Existing
DC	Scranton, PA	7	New (Expansion)
DC	Dallas, TX	8	Existing
DC	Montgomery, AL	9	Existing
DC	Reno, NV	10	Existing
DC	Reno, NV	11	New (Expansion)
DC	Toronto, Canada	12	Existing
DC	Newark, NJ	13	New
DC	Miami, FL	14	New
DC	Memphis, TN	15	New
DC	Charlotte, NC	16	New
DC	Atlanta, GA	17	New
DC	Ontario, Canada	18	New
DC	Seattle, WA	19	New
DC	Louisville, KY	20	New
IDC	Ashland, KY	21	Existing
IDC	Memphis, TN	22	New

Type	Location	ID	Existing/New
IDC	Miami, FL	23	New
Rental Region	Central	24	Existing
Rental Region	Central Plains	25	Existing
Rental Region	E. Central	26	Existing
Rental Region	E. Canada	27	Existing
Rental Region	Florida	28	Existing
Rental Region	Great Lakes	29	Existing
Rental Region	Mid-Atlantic	30	Existing
Rental Region	Mid-South	31	Existing
Rental Region	Midwest	32	Existing
Rental Region	Mountain	33	Existing
Rental Region	N. Central	34	Existing
Rental Region	Northeast	35	Existing
Rental Region	Northwest	36	Existing
Rental Region	S. Central	37	Existing
Rental Region	Southeast	38	Existing
Rental Region	Southwest	39	Existing
Rental Region	Western	40	Existing

- Objective Function: Minimize costs while satisfying demand from each customer region
- Constraints:

- Must maintain flow balance for intermediate nodes
- Demand must be met for each customer region
- Flow along each arc cannot be negative
- Product families must flow through designated network path (e.g. utilization of IDC or direct shipments to regional DC)
- Product families must use designated transportation mode (e.g. LTL or TL)
- Capacity at each IDC and DC cannot be exceeded
- Linking constraints are needed for all IDC and DCs
    - Binary variables for each DC will be used to determine whether or not to use it. 1 represents yes, 0 for no.
    - Incorporate big M
- Non-Negativity

Thus, the model can be stated as follows:

Objective Function:

$$
\begin{aligned}
Min:\ & \sum_{j} \mathrm{F_j}(\mathrm{DF_j} + DO_j + DE_j) + (\mathrm{F_j} - 1)(-DC_j) + \sum_{l} \mathrm{F_l}(\mathrm{DF_l} + DO_l + DE_l) + (\mathrm{F_l} - 1)(-DC_l) \\
& + \sum_{k=1}^{4} \sum_{\mathrm{i,j}} \frac{\mathrm{X_{ijk}}}{\mathrm{A_k}}(\mathrm{DV_j}) + \sum_{k=5}^{8} \sum_{\mathrm{i,l}} \frac{\mathrm{X_{ilk}}}{\mathrm{A_k}}(\mathrm{DV_l}) + \sum_{k=1}^{4} \sum_{\mathrm{j,l}} \frac{\mathrm{X_{jlk}}}{\mathrm{A_k}}(\mathrm{DV_l}) + \sum_{k=1}^{4} \sum_{i,j} RL_{ij} X_{ijk} B_k \\
& + \sum_{k=7}^{8} \sum_{i,l} RL_{il} X_{ilk} B_k + \sum_{k=1}^{4} \sum_{j,l} RL_{jl} X_{jlk} B_k + \sum_{k=1-4,7,8} \sum_{l,m} RL_{lm} X_{lmk} B_k \\
& + \sum_{k=5}^{6} \sum_{i,l} RT_{il} X_{ilk} B_k + \sum_{k=5}^{6} \sum_{l,m} RT_{lm} X_{lmk} B_k
\end{aligned}
$$

Subject To:

$$
\left.
\begin{aligned}
& \sum_{i} X_{ijk} = \sum_{l} X_{jlk} \quad for\ k = 1-4\ and\ \forall\ j \\
& \sum_{j} X_{jlk} = \sum_{m} X_{lmk} \quad for\ k = 1-4\ and\ \forall\ l \\
& \sum_{i} X_{ilk} = \sum_{m} X_{lmk} \quad for\ k = 5-8\ and\ \forall\ l
\end{aligned}
\right\} \text{Flow Balance}
$$

$$\sum_{l} X_{lmk} \geq RD_{mk} \ \forall m,k$$ Satisfy Demand

$$\sum_{m}\sum_{k}\frac{X_{lmk}}{A_k} \leq C_l \quad for\ l = 5-13\ and\ 16-20$$

$$\left[\sum_{i}\sum_{k=5}^{8}\frac{X_{i,4,k}}{A_k}\right] + \left[\sum_{i}\sum_{k=1}^{4}\frac{X_{i,21,k}}{A_k}\right] + \left[\sum_{j=22}^{23}\sum_{k=1}^{4}\frac{X_{j,4,k}}{A_k}\right] \leq C_4$$

$$\left[\sum_{i}\sum_{k=5}^{8}\frac{X_{i,14,k}}{A_k}\right] + \left[\sum_{i}\sum_{k=1}^{4}\frac{X_{i,23,k}}{A_k}\right] + \left[\sum_{j=21}^{22}\sum_{k=1}^{4}\frac{X_{j,14,k}}{A_k}\right] \leq C_{14}$$

$$\left[\sum_{i}\sum_{k=5}^{8}\frac{X_{i,15,k}}{A_k}\right] + \left[\sum_{i}\sum_{k=1}^{4}\frac{X_{i,22,k}}{A_k}\right] + \left[\sum_{j=21,23}\sum_{k=1}^{4}\frac{X_{j,15,k}}{A_k}\right] \leq C_{15}$$

DC Capacity Constraints

$$\sum_{i}\sum_{k} X_{ijk} \leq F_j M \quad \forall j$$

$$\sum_{m}\sum_{k} X_{lmk} \leq F_l M \quad \forall l$$

Linking Constraint

$$F_j \in \{0,1\} \quad \forall j$$

Binary Constraint

$$F_6 \geq F_7$$

$$F_{10} \geq F_{11}$$

Conditional Expansion

$$X_{ijk} \geq 0 \quad for\ all\ ijk$$

$$X_{jlk} \geq 0 \quad for\ all\ jlk$$

$$X_{ilk} \geq 0 \quad for\ all\ ilk$$

$$X_{lmk} \geq 0 \quad for\ all\ lmk$$

Non-Negativity

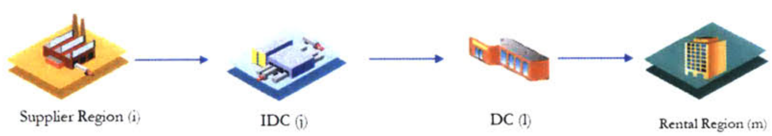
4.2. The Company's Supply Chain Network Data

Historical data received from The Company's supply chain team provided the input and constraints for the model.

4.2.1. Product Family Data

The Company's product line was allocated into three product families representing eight basic item types. Each product family was assigned a network path and transportation mode within the company's supply chain network. These designated paths are shown in Figure 4.

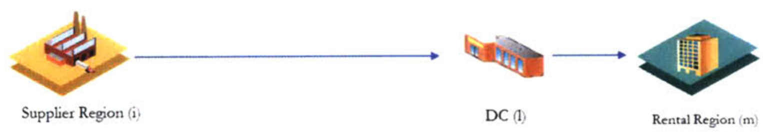
Rental



Rental Product Flow Conditions

Product Families (k)	IDC Requirement?	Transportation Method
1-4	Yes	LTL

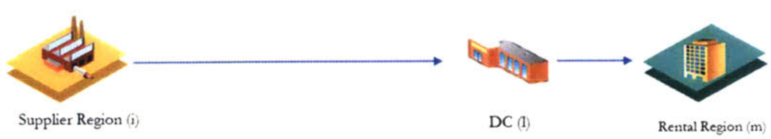
Facility Services (FS)



FS Product Flow Conditions

Product Families (k)	IDC Requirement?	Transportation Method
5-6	No	Truckload

First Aid & Safety (FAS)



FAS Product Flow Conditions

Product Families (k)	IDC Requirement?	Transportation Method
7-8	No	LTL

Figure 4 Product Family Flow Pattern

Rental product family items must flow through an IDC and use LTL freight. Facility services product family items (restroom cleaning supplies, mat service, mops, towels) bypass the IDC and ship directly to regional DCs using TL freight. The FAS (First Aid & Safety) product family items also bypass the IDC but ship directly to regional DCs using LTL freight.

Table 5 provides capacity unit translations for each product family item.

Table 5 Capacity Unit Conversions

Number	Family	IDC or Not	Mode	units (each)	DC Capacity Units (eaches per box)	Pounds (per unit)
Family 1	Rental	Y	LTL	1	36	0.98
Family 2	Rental	Y	LTL	1	12	2.08
Family 3	Rental	Y	LTL	1	96	0.188
Family 4	Rental	Y	LTL	1	30	1.33
Family 5	FS	N	TL	1	1	0.24
Family 6	FS	N	TL	1	1	3.47
Family 7	FAS	N	LTL	1	72	0.03
Family 8	FAS	N	LTL	1	1	22

4.2.2. Supplier Data

Product flowing into The Company's supply chain network was modeled to arrive from three supplier regions. For modeling purposes, supplier regions are synonymous with ports. The ports of Miami, Seattle and Newark are the three most heavily utilized import locations for the company's distribution of goods.

Table 6 shows the number of units flowing into the system by supplier region and product family. Again, units are converted into standard capacity units to standardize accounting for DC handling costs.

Table 6 Supplier Region Capacity

Supplier Data	Supplier Region 1	Supplier Region 2	Supplier Region 3	Sum of units	"capacity units" (standard boxes)
Port	Miami	Seattle	Newark		
Capacity (units/year/family) - Sik Family 1	11,843,760	1,863,498	99,825	13,807,083	383,530
Capacity (units/year/family) - Sik Family 2	419,658	86,378	803,345	1,309,381	109,115
Capacity (units/year/family) - Sik Family 3	12,179	67,980	-	80,159	835
Capacity (units/year/family) - Sik Family 4	11,099,118	10,772	1,136,707	12,246,597	408,220
Capacity (units/year/family) - Sik Family 5	242,915	226,017	93,383	562,315	562,315
Capacity (units/year/family) - Sik Family 6	2,025,967	353,058	929,406	3,308,431	3,308,431
Capacity (units/year/family) - Sik Family 7	21,461,665	3,958,429	322,057,816	347,477,910	4,826,082
Capacity (units/year/family) - Sik Family 8	331,268	53,518	2,749,465	3,134,251	3,134,251

4.2.3. DISTRIBUTION CENTER DATA

The Company provided distribution center throughput capacities for existing locations, as well as estimated expansion capacities for potential new buildings. The Finance Department assisted in generating realistic DC expenses for fixed, variable, opening, closing and expansion costs for each existing and expansion warehouse location. As the IDC opening cost and all IDC and DC closing costs were quite high, we allocated them over a five year period. These figures can be found in Table 7.

Table 7 Distribution Center Capacity and Costs

Distribution Center Data	4	5	6	7	8	9	10
Type	DC	DC	DC	DC	DC	DC	DC
Location	Ashland	Mason	Scranton	Scranton Expansion	Dallas	Montgomery	Reno
Existing or New?	Existing	Existing	Existing	New (Expansion)	Existing	Existing	Existing
Capacity ("capacity units"/year) - Cj	2,550,000	2,390,625	478,125	318,750	3,825,000	478,125	478,125
Fixed Costs ($/per year) - DFj	$2,315,080	$1,426,176	$623,599	$311,800	$2,452,353	$644,577	$435,450
Variable Cost ($/"capacity unit") - DVj	$1.40	$1.57	$1.06	$1.06	$0.92	$1.21	$1.29
Opening Cost ($) - Doj							
Closing Cost ($) - DCj	-$443,563	-$367,770	-$199,567		-$199,567	-$199,567	-$199,567
Expansion Cost ($) - Dej				$125,000			

	11	12	13	14	15	16	17
Type	DC	DC	DC	DC	DC	DC	DC
Location	eno Expansio	Toronto	Newark	Miami	Memphis	Charlotte	Atlanta
Existing or New?	w (Expansio	Existing	New	New	New	New	New
Capacity ("capacity units"/year) - Cj	318,750	478,125	478,125	478,125	478,125	478,125	478,125
Fixed Costs ($/per year) - DFj	$217,725	$685,662	$837,973	$674,206	$479,348	$534,255	$577,942
Variable Cost ($/"capacity unit") - DVj	$1.29	$1.14	$1.50	$1.39	$1.24	$1.32	$1.34
Opening Cost ($) - Doj				$325,000	$325,000	$325,000	$325,000
Closing Cost ($) - DCj		-$199,567					
Expansion Cost ($) - Dej	$125,000						

	18	19	20	21	22	23
Type	DC	DC	DC	IDC	IDC	IDC
Location	Ontario	Seattle	Louisville	Ashland	Memphis	Miami
Existing or New?	New	New	New	Existing	New	New
Capacity ("capacity units"/year) - Cj	478,125	478,125	478,125			
Fixed Costs ($/per year) - DFj	$984,756	$836,331	$516,167			
Variable Cost ($/"capacity unit") - DVj	$1.55	$1.50	$1.29	$1.40	$1.24	$1.39
Opening Cost ($) - Doj	$325,000	$325,000	$325,000		$1,352,593	$1,530,735
Closing Cost ($) - DCj				-$199,567		
Expansion Cost ($) - Dej						

Additionally, we had to consider the flow through the distribution center. The Capacity figures in Table 8 represent each facility's flow. To calculate this figure, we identified the number of trucks and less than truckload that each dock could handle per day and multiplied by the number of days worked each year and the number of capacity units that can fit on a truck.

4.2.4. Rental Region Data

Customer locations, known as rental regions in the model, were assigned to 17 geographic areas in the country. Customer demand for each rental region is shown for the 17 product families in Table 8.

Table 8 Rental Region Demand

Rental Location Data	Rental Region 24	Rental Region 25	Rental Region 26	Rental Region 27	Rental Region 28	Rental Region 29
Region	Central	Central Plains	East Central Group	Eastern Canada	Florida	Great Lakes
Rental Demand (units/year/family) - RDjk k=1	1,410,422	1,379,311	1,258,819	812,976	1,272,931	2,255,883
Rental Demand (units/year/family) - RDjk k=2	151,168	129,250	152,922	191,257	29,902	176,266
Rental Demand (units/year/family) - RDjk k=3	5,537	3,954	5,284	54,877	3,107	12,910
Rental Demand (units/year/family) - RDjk k=4	1,218,750	1,039,790	1,208,835	636,133	1,120,501	2,118,144
FS Demand (units/year/family) - RDjk k=5	43,715	40,938	29,448	29,953	34,276	52,491
FS Demand (units/year/family) - RDjk k=6	350,178	317,883	302,247	90,565	193,213	625,704
FAS Demand (units/year/family) - RDjk k=7	420,010	-	-	-	-	-
FAS Demand (units/year/family) - RDjk k=8	34,505	-	-	-	-	-

Rental Location Data	Rental Region 30	Rental Region 31	Rental Region 32	Rental Region 33	Rental Region 34	Rental Region 34	Rental Region 35
Region	Mid Atlantic Group	Mid South	Midwest	Mountain	North Central	North Central	Northeast
Rental Demand (units/year/family) - RDjk k=1	2,827,623	1,409,233	1,477,271	1,133,063	1,771,793	1,771,793	1,209,953
Rental Demand (units/year/family) - RDjk k=2	266,320	139,513	106,638	220,583	190,679	190,679	122,656
Rental Demand (units/year/family) - RDjk k=3	22,053	4,342	16,171	6,064	11,679	11,679	12,288
Rental Demand (units/year/family) - RDjk k=4	2,596,238	1,384,384	1,364,005	863,107	1,471,072	1,471,072	1,034,791
FS Demand (units/year/family) - RDjk k=5	77,625	38,603	30,864	55,449	56,902	56,902	35,792
FS Demand (units/year/family) - RDjk k=6	660,711	158,797	345,476	253,796	587,424	587,424	354,604
FAS Demand (units/year/family) - RDjk k=7	-	-	-	-	552,229	552,229	903,448
FAS Demand (units/year/family) - RDjk k=8	-	-	-	-	21,952	21,952	47,187

Rental Location Data	Rental Region 36	Rental Region 37	Rental Region 38	Rental Region 39	Rental Region 40	Rental Region 39	Rental Region 40
Region	Northwest	South Central	Southeast	Southwest	Western	Southwest	Western
Rental Demand (units/year/family) - RDjk k=1	842,142	1,123,571	1,547,134	1,863,436	1,272,499	1,863,436	1,272,499
Rental Demand (units/year/family) - RDjk k=2	146,377	116,541	125,453	182,686	121,132	182,686	121,132
Rental Demand (units/year/family) - RDjk k=3	3,035	3,837	10,178	4,044	3,289	4,044	3,289
Rental Demand (units/year/family) - RDjk k=4	578,749	1,032,158	1,476,264	1,342,574	1,026,717	1,342,574	1,026,717
FS Demand (units/year/family) - RDjk k=5	45,184	35,975	41,689	59,525	46,392	59,525	46,392
FS Demand (units/year/family) - RDjk k=6	286,937	276,534	286,470	458,946	188,396	458,946	188,396
FAS Demand (units/year/family) - RDjk k=7	-	-	667,946	-	799,759	-	799,759
FAS Demand (units/year/family) - RDjk k=8	-	-	44,870	-	29,837	-	29,837

4.3. Model Iterations

Once the model was built, with the mini model constraints and the data provided by The Company, we ran iterations to analyze the model's behavior and key variables and constraints.

4.3.1. Current State Model

To ensure that the model reflected The Company's business and constraints, we first had to train the model. This involved forcing all of the new distribution center locations closed, to see if the volume would flow through the model network in a way that approximately matched The Company's current product flow. The Company acknowledged that minimal mathematical and financial studies had been done when opening new locations or shifting volume, so that the model would likely run a more cost efficient operation than the company currently does.

The model successfully allocated products throughout the current DCs, with the most volume running through Ashland, as it also serves as the only IDC for The Company. This is consistent with current operations, but proved to not be the optimal solution

4.3.2. FINANCE OPTIMIZED MODEL

Two versions of the initial optimization model were run to account for finance's preference to recognize all opening, closing, and expansion costs in the first year. The model is a single-period model, which means it cannot distinguish one-time costs from annual costs. With opening costs as high as $7 million, this means the model would have to find savings exceeding this amount to validate opening a new IDC. As expected, when we ran this iteration, the model did not open any new locations. The optimized solution filled every DC to maximum flow capacity with the exception of Mason, which has a capacity similar to Ashland's but higher variable costs and cannot also operate as an IDC.

4.3.3. FIVE YEAR COSTING OPTIMIZED MODEL

To truly see the impact of the optimization tool, we spread the IDC opening and all of the IDC and DC closing costs over five years. This provides the model more decision making flexibility, as it only needs to find savings of a fifth of an opening or closing cost in order to validate changes to the network. This model opened Miami as a new DC and IDC, and closed Mason and Toronto. The reason for the shift was the transportation savings, as more supplier volume comes through Miami than either of the other ports.

4.3.4. INCREASING DEMAND MODELS

Continuing with the IDC opening cost and the IDC and DC closing cost five year allocation, we ran iterations for a 10% and a 20% increase in demand. The difference between the two scenarios was unexpected, but illuminated some crucial points for The Company to consider in mapping its future.

With 10% demand growth across all product families and regions, the model found a similar solution to the Five Year Costing Optimized Model. Additional demand was placed into the Ashland IDC and into Atlanta. The model also kept Toronto open, which it had not done in the model based on historical demand.

When we increased demand an additional 10% across the board, there was a sizeable shift toward consolidation in larger facilities. Ashland, Scranton, Reno, and Dallas were filled to capacity, while Miami was opened as an IDC and also completely filled. Mason, for the first time, was also nearly filled to capacity. Toronto, though kept open at the 10% demand increase, was closed at the 20% increase, as paying the additional fixed costs for its smaller size did not compensate for the increased variable costs to put all of the additional volume in Mason.

4.3.5. Only Variable Costs Model

To continue analyzing the impact of variable costs on the model, we ran a simulation excluding all fixed, opening, closing, and expansion costs. Again, the IDC opening costs and the IDC and DC closing costs were spread over a five year time period, and demand was reset to its historical levels. The solution spread the products widely across a mix of new and existing DCs and IDCs. Ashland was used minimally, and Mason not at all. Scranton and Reno were expanded, and many of the smaller DCs were filled to capacity. Dallas, the largest DC, was still also filled in entirety due to its extremely low variable costs. Newark, Miami, Seattle, Charlotte, and Louisville were also opened due to their lower variable costs, and in the case of Seattle and Miami, due to their close proximity to the supplier ports.

4.4. Recommendation

The Company's current network is sufficient for its needs. However, it is not optimal. Full results comparing the model variations that were run can be found in Appendix 1.

As the company continues to grow, it will need to consider larger buildings in centralized locations where variable costs are low. Prior to opening new facilities, we are confident that additional financial analysis is needed to confirm the fixed, variable, and opening and closing costs. Large facilities are only most desirable and outweigh marginal late rate differences when demand requires additional capacity, so accurate financial figures will be vital to selecting the most cost efficient location.

Additionally, The Company may want to run sensitivity analysis on any volume shifts. Should less volume come in through one region or another, this may shift the desirable product mix within each DC. Ultimately, it seems that in the Company's current state, the larger question for additional research is not where to open a facility, but where to place its products within its current network.

Finally, The Company should consider the impact of using different supplier ports. Miami was selected by nearly every model run because of its close proximity to the largest supplier port. If The Company considered other southeastern ports such as Charlotte, Savannah, or Atlanta, the model would likely recommend opening DCs and IDCs in this region and shifting volume accordingly.

5. DISCUSSION

The data analysis in Section 4 provides the background for the findings and recommendations in this section. Recommendations are based on the essential question at hand: how to design the most efficient product flow for The Company's cost savings. Consistent with Nagurney's (2012) findings on the effectiveness of optimization model for network structure questions, our model successfully identified the most cost efficient solution for The Company. Such projects are vital to supply chains everywhere as companies are constantly pressured to reduce costs and increase responsiveness in the ever-growing marketplace.

5.1. Key Findings

The initial model was created to accurately reflect the shipping and distribution limitations within The Company, such as the infeasibility of mode shifting, mentioned in section 2. Owen and Daskin (1998) stressed the importance of considering facility capacity and costs, which proved to be a significant variable in our model due to the high costs associated with facility operations and movements and the binding constraints imposed by facility capacities. Had we let the model ignore the size of a distribution center, it would have suggested moving all product through one distribution center, which is not a realistic or feasible solution for many companies, including The Company.

Next we will discuss how companies can develop similar optimization network models and additional variables excluded from this model that companies should consider.

5.2. Recommendations for Model Structure and Analysis

Network optimization models are extremely important for any company desiring to lower its operating and logistics costs. With data from the carriers and financial teams, models can tell a company where the tradeoff of lower lane rates and higher operating costs breaks even. The company can also force a certain number of distribution centers open or closed in the model to analyze a more centralized or decentralized strategy. However, to successfully implement such a strategy, companies need to ensure accurate data collection and carefully consider their specific constraints and opportunities.

5.2.1. TRANSPORTATION LIMITATIONS

Due to The Company's distribution requirements, there was no opportunity to aggregate the rental less-than-truckload quantities into full truckloads. Many networks with intermediate distribution center locations are created for such aggregation opportunities, which significantly lowers transportation costs. Any company creating a similar model would benefit greatly from considering the cost savings of aggregation or mode switching, as highlighted by Ahmadizar & Zeynivand, 2014. If lead time allows, intermodal transportation should also be considered for further savings. However, any model that allows products to switch transportation modes should consider the lead time implications. This is especially crucial where high service levels are of primary importance, such as in the Petri net technique (Zhang, You, Jiao, & Helo, 2009).

Our model also assumed linear lane rates per pound. For example, if one lane cost $0.05 per pound, then a five-pound shipment would simply cost $0.05*5, or $0.25. However, less than truckload carriers operate with weight breaks, where at certain weights the rate per pound changes. If the shipments flowing through the network are approximately the same weight, the linear assumption is acceptable. Reverse logistics or backhaul opportunities may also be important influencers on lane rates and the cost per pound used in a model, as proposed by Ozceylan & Paksoy (2012) and should be considered if there is opportunity to provide the carrier with returning volume.

5.2.2. Network Limitations

The Company's network currently requires Rental Garments to go through the intermediate distribution center location due to supplier agreements and capacity restrictions at the final distribution centers. Further cost savings might be realized from removing this intermediary point; additional analysis of the costs associated with an intermediary stage should be analyzed by allowing the model to select whether or not to pass through the point.

5.2.3. Demand Considerations

The model run for this thesis assumed constant historical demand, as the primary goal was to compare the current network with a current optimal network. Many researchers, such as Pirkul and Jayaraman (1998), have made the same assumption due to the risk introduced with adding a forecasting dimension. However, if a company is in a growth cycle or experiences location-based supplier or consumer volume shifts, there will be significant impacts on the transportation costs. If a company expects to experience significant growth in a new region, they may want to consider running multiple iterations of the model with varying levels of volume to understand the model's sensitivity to such regional shifts.

This section reviewed the results variance in The Company's model and considerations for companies desiring to run similar optimization analysis. Section 6 will present our final thoughts and highlight our key recommendations.

6. CONCLUSION

By developing an optimization model for our thesis sponsor, we found a specific desired distribution network layout for one set of parameters, and identified how different variables can have a large impact on the cost decision. The significant costs associated with distribution center operations and their opening and closing weighs heavily on the decision and should be scrutinized carefully.

6.1. Implications for The Company

While distribution center costs are sizeable and commonly recognized as a significant investment, we did not recognize how significant they would be to The Company's results. Large, centralized facilities may not be the most financially desirable choice for the company if demand does not fully utilize the facility. Before fully considering any model implications, though, The Company needs to confirm financial estimates. They should also run additional analysis comparing larger capacity locations near other ports in the US, such as utilizing Atlanta or Savannah, where less expensive labor rates may yield an even less expensive solution.

6.2. Takeaways and Future Developments

As mentioned in Chapter 5 The Company's optimization model yields many lessons from which other companies can benefit, and many omitted factors which companies may want to consider.

Transit time was not included in this model as mode switching was not permitted. Any company with strict transit requirements or that wants to consider different mode options should take into account the variance in transit time. Additionally, mode switching and consolidation can allow for significant cost savings, which a company should review as this may lead to additional savings (and could even be worth a transit delay.) A company should also decide whether a simple model will suffice, or if the model needs to consider additional complexities such as non-linear lane rates, or changes in demand and supplier regions and volume.

With these specific considerations and precise distribution center financial estimates, any company can successfully analyze its network, in both its current and future state, with a similar optimization model. It generates high level conversations regarding the optimal network setup, as well as the factors driving costs in each DC or region, such as lane rates or the variable costs at a specific DC, that can lead to additional cost saving projects.

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Appendix 1 Model Results

									Model Simulations (Flow in Capacity Units)				
Location	IDC/DC	Existing, New, or Expansion	Capacity	Fixed Cost	Variable Cost	Opening Cost	Closing Cost*	Expansion Cost	Finance Model**	5 Year Costs	5YC 110% Demand	5YC 120% Demand	No Fixed, Open, Close, Expand Costs
Ashland	DC	Existing	2,550,000	$2,315,080	$1.40		($443,563)		2,550,000	2,285,107	2,481,742	2,550,000	814,092
Mason	DC	Existing	2,390,625	$1,426,176	$1.57		($367,770)		53,857	-	-	2,200,253	-
Scranton	DC	Existing	478,125	$623,599	$1.06		($199,567)		478,125	478,125	478,125	478,125	478,125
Scranton	DC	Expansion	318,750	$311,800	$1.06			$125,000	-	318,750	-	-	318,750
Dallas	DC	Existing	3,825,000	$2,452,353	$0.92		($199,567)		3,825,000	3,825,000	3,825,000	3,825,000	3,825,000
Montgomery	DC	Existing	478,125	$644,577	$1.21		($199,567)		478,125	478,125	478,125	-	478,125
Reno	DC	Existing	478,125	$435,450	$1.29		($199,567)		478,125	478,125	478,125	478,125	478,125
Reno	DC	Expansion	318,750	$217,725	$1.29			$125,000	-	-	-	-	62,608
Toronto	DC	Existing	478,125	$685,662	$1.14		($199,567)		478,125	-	478,125	-	478,125
Newark	DC	New	478,125	$837,973	$1.50				-	-	-	-	161,062
Miami	DC	New	478,125	$674,206	$1.39	$325,000			-	478,125	478,125	478,125	478,125
Memphis	DC	New	478,125	$479,348	$1.24	$325,000			-	-	-	-	478,125
Charlotte	DC	New	478,125	$534,255	$1.32	$325,000			-	-	-	-	96,079
Atlanta	DC	New	478,125	$577,942	$1.34	$325,000			-	-	478,125	-	-
Ontario	DC	New	478,125	$984,756	$1.55	$325,000			-	-	-	-	-
Seattle	DC	New	478,125	$836,331	$1.50	$325,000			-	-	-	-	29,837
Louisville	DC	New	478,125	$516,167	$1.29	$325,000			-	-	-	-	356,011
Memphis	IDC	New	see Memphis DC		$1.24	1,352,592*			-	-	-	-	478,125
Miami	IDC	New	see Miami DC		$1.39	1,530,735*			-	478,125	478,125	454,110	478,125
Ashland	IDC	Existing	see Ashland DC		$1.40		($199,567)		1,623,868	1,145,743	1,308,129	1,470,516	814,092
Obj Func Min Cost									$37,066,311	$30,566,311	$34,069,899	$37,279,298	$24,882,127

* Closing costs allocated over five years
** The model run for the finance team assumed all DC costs were realized in year one. Thereby, the financial results cannot be compared with those run against the five year disbursements