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MULTI-CRITERIA SUPPLY CHAIN NETWORK DESIGN FOR FRESH PRODUCE

A Thesis in

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by

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ABSTRACT

Due to the numerous waste and disposal of food products and the high storage and transportation cost, the fresh produce market has a low profit margin. This thesis studied a three-stage supply chain distribution network design problem with multiple plants, multiple distribution centers, multiple customer zones and multiple products, aiming to reduce the annual supply chain cost and investment cost as well as to improve the freshness of products by investing in owned distribution centers and designing optimal distribution networks.

To solve the supply chain distribution network design problem, firstly a Mixed-integer Linear Programming (MILP) model with three conflicting objectives is proposed. Then a Weighted Sum Method is considered as the approach to deal with the multi-criteria problem. That is generating different optimal solutions under different weight combinations assigned to the objective functions. The functionality and applicability of the model and method is illustrated by implementing them in a case study of fresh apple and strawberry with the plants, distribution centers and customer zones all over the United States. Finally, some efficient solutions and trade-offs among three criteria are provided to support decision making.

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Chapter 1

INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

The participants in a food supply chain for fresh products may include farmers, wholesalers, retailers and their service suppliers like the third party logistics, and the main process involved in such food supply chain are handling, conditional storing, packing and delivering of these goods (Van der Vorst, 2000). Nowadays, the structure of the food supply chain has become more complex due to the increasing number of players participating in the food supply chain. As the global market expanding, more importers and exporters are involved and more retailers bypass wholesalers to source produce directly from farmers or producers to reducing their purchasing cost. With the increasing price of fresh produce from farmers, the profit margin of the fresh produce industry has continued to remain slim although the demand is increasing. Also, the significant waste and spoilage in the food supply chain reduced revenues. According to a report provided by ChainLink Research (2011), in the U.S. alone, approximately 23%-25% of fruits and vegetables are lost post-harvest, resulting in a 25%–50% loss of the total economic value due to reduced quality. With increasing global competition and the associated greater distances between food production sites and consumption locations, there is a need to access and design integrated supply chain distribution networks that can meet the requirements for fresh produce with lower cost. (Yu and Nagurney, 2012).

The challenge for managing fresh produce is that product quality deteriorates significantly over time depending on the environment conditions of the storage and transportation facilities in the supply chain (Blackburn and Scudder, 2009). To extend the shelf life of products, they usually have to be processed, stored and transported under a low temperature to reduce the deterioration of food quality, which leads to a higher inventory cost and transportation cost in the supply chain for fresh produce. So, the efficiency of the supply chain is an essential consideration for the supply chain design problem. To reducing the inventory holding cost and storage time of products, the wholesalers and retailers are willing to increase the inventory turns, hence reduce the average inventory level. However, with less inventory are held, it may have a negative effect on the response time to customers, which will result in a decrease in customer service level. For the sake of the perishability of fresh produce, the transportation time between facilities significantly influent the freshness of the product, which then impact the customers' satisfactions. Given the characteristics of fresh produce supply chains, responsiveness is also a key measurement of the supply chain performance. A shorter lead time from suppliers to customers can reduce the response time to customer and improve the freshness of products. This thesis intends to design a supply chain distribution network with a better performance in both efficiency and responsiveness.

An effective approach for solving the supply chain problem described above is optimization modeling. A major application area of supply chain optimization is production and inventory planning. To stay competitive in the market, it is very important for manufacturers to design optimal production schedules and inventory levels that can meet the customers' demand with a minimum manufacturing cost. Supply chain distribution network design optimization is another highly researched area. Most of the research focus on the optimal numbers, capacities and locations of facilities, and some of them also consider the inventory level, supplier selection and routing plans. Mixed-integer programming (MIP) models are the common models used to obtain the optimal solutions of such problems and the common objective of these models is to minimize the total cost occurred in the distribution network, that is usually involves making tradeoffs between fixed opening costs of facilities and transportation costs (Pishvaee et al. 2011). However, three criteria are taken into consideration in the decision-making process in this thesis, because the developed model aim to not only improving supply chain performance but also reducing the investment of the refrigerated distribution centers.

1.2 Problem Statement

1.2.1 Fresh produce supply chain network

The activities associated with a food supply chain network include production, processing, storage, distribution and disposal of food products. In this thesis, a three-stage supply chain multiple suppliers, multiple distribution centers (DCs) and multiple customer zones (CZs) is taken into consideration. The network of the supply chain is shown in Figure 1.1

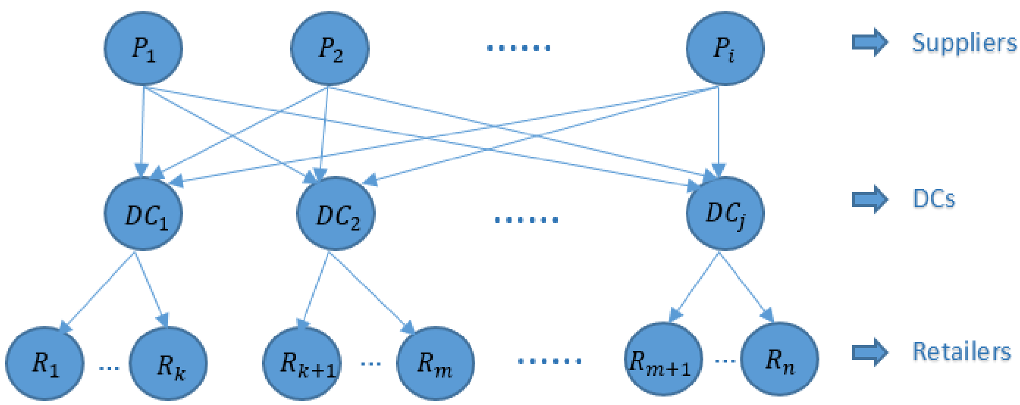

Figure 1.1. Three-stage Supply Chain Network

The first stage of the supply chain is responsible for the processing of the fresh produce, such as cleaning, cooling and packing, and the distribution centers in the second stage are designed for the storage and delivery products to customer zones in the third stage. The demands in the customer zones are assumed to be deterministic and are all met by the shipments from distribution centers. There is an assignment problem between the last two stages and a customer zone can be assigned to only one distribution center.

1.2.2 Objectives

The main objective of this thesis is to design an optimal supply chain distribution network for fresh produce that can best comprise three criteria. The first one is total annual cost over the supply chain including transportation cost and operating cost of distribution centers. The second one is the freshness of products which is estimated by the mean lead time of products between suppliers and distribution centers. The last one is the investment of the refrigerated distribution centers. The key strategic decisions need to make includes (1) the appropriate number of invested distribution centers, (2) the size and location of each distribution center, (3) the assignment of distribution centers to the customer zones and (4) the annual shipping quantity of products through the supply chain network.

1.2.3 Case study

To better understand the supply chain network design problems and the trade-offs among three criteria, a case considering apple and strawberry distribution network over the US is analyzed by implementing the developed mathematical optimization model. The supply chain system of the problem consists 48 production plants, 48 candidate distribution centers and 202 aggregated customer zones in the US, exclude the Hawaii and Alaska states. The results of the supply chain model will support the decision maker to evaluate several efficient distribution networks.

1.3 Thesis Outline

This thesis is organized as follows: Chapter 2 consists of the literature review of the fresh produce supply chain, multi-echelon supply chain network design and multi-criteria optimization problems; Chapter 3 introduces a Multi-criteria Mixed-integer Programming Model and solving approaches for the optimal design of the three-stage supply chain network for fresh produce; In Chapter 4, a case study about distribution network design for apple and strawberry in the US is presented. Through the analysis of solutions obtained by solving the mathematical model, some insights about the trade-offs among objectives are provided in Chapter 5. Chapter 6 presents some conclusions and future research scope for this study.

Chapter 2

LITERATURE REVIEW

This chapter summarizes the research in the field of the supply chain distribution network design that have been studied in this thesis. There has been lots of previous work on the supply chain design and significant ongoing research is being carried out to develop efficient models that incorporate the integration of supply chain and multi-criteria. Simchi-Levi et al., (1999) mentioned that network configuration may involve issues relating to production plant, distribution center and retailer, and the distribution network design problems generally fall into the strategic level supply chain design, which means the decisions made in such problems have an impact on the performance of supply chain for a long time, such as the location and capacity of facilities and transportation mode. Mixed-integer Programming (MIP) models are highly used in modeling the distribution network design problems and range from simple uncapacitated facility location models to complex capacitated multi-stage or multi-product models (Pishvaee et al. 2011). The literature about the optimization models and solving methods for distribution network design problems are presented in two aspects, single objective and multiple objectives.

2.1 Single Objective Distribution Network Design

The common objective of distribution network models is minimizing cost. The basic supply chain design problem only considered single stage facility locations. Erlenkotter (1985) presented an integer programming model and a dual solution procedure to determine the location of uncapacitated facilities. Mazzola and Neebe (1999) applied Lagrangian relaxation to solve a multi-product capacitated facility location problem with the choice of facility type. Some of the research considered budget as a constraint and minimizing delivery distance as the objective on the single stage facility location problems. For example, Wang et al. (2003) worked on the optimal decision of opening or closing facilities with constraints on the budget and the total number of facilities.

Melkote and Daskin (2001) investigated a MIP model to simultaneously optimize uncapacitated facility locations and transportation network, and provided a LP relaxation for solving the model, and then they considered capacity constraint on facilities. Teo and Shu (2004) considered a warehouse-retailer network system. The problem is to determine the optimal facility locations and numbers, the optimal allocation plan from warehouse to retailers and the optimal inventory policy with minimum inventory, transportation, and facility location costs. Similarly, Prmeijn et al. (2007) formulated the integrated two stages supply chain network design problem as a set-covering model and presented a genetic modeling approach to optimize the network configuration and inventory policies for both the plants and DCs, considering a single sourcing policy for the customer zones.

Amiri (2006) studied a three stages supply chain network design problem, aiming to find optimal numbers, locations and capacities of plants and warehouses and strategic distribution plans between facilities that can satisfy all the demand at a minimum total cost over the supply chain. To solve the problem, a MIP model is formulated and a heuristic solution procedure is provided. Rabbani et al. (2008) incorporated multi-product in their model for designing distribution network. Cordeau et al. (2006) presented a model formulation that integrates location and capacity choices for facilities, product flows as well as transportation mode selection for a logistics network design problem encountered in deterministic, single-country, and single-period contexts. Tisakis and Papageorgiu (2008) proposed a Mixed-integer Linear Programming (MILP) model to determine the optimal design and operation of multi-product, multi-echelon production allocation and distribution network with introducing financial constraints on the top of usually used operational constraints, where the operational constraints ensure the quality, production and supply restriction, production allocation and work-load balance and financial constraints include production cost, transportation cost and duties for the material flowing within the network subject to exchange rates. Then Tisakis et al. (2011) considered the demand uncertainty in the model, which is captured in terms of a number of likely scenarios that are possible to happen during the lifetime of the network, and applied the model to a large-scale European wide distribution network.

Moreover, Hasani et al. (2012) developed a close-loop supply chain network design model with interval uncertainty in final products demand and purchasing cost for perishable goods in agile manufacturing and the uncertainty is handled via an interval robust optimization technique. The storage of product in warehouse follows a first in first out policy due to the perishability.

2.2 Multi-objective Distribution Network Design

Some of research considered multiple criteria when modeling a supply chain distribution network, especially for some specialized application like green supply chain and food supply chain. Besides minimizing total cost, minimizing response time or lead time and minimizing carbon emission through the supply chain may also be taken into account.

Nozick and Turnquist (2001) provided an integer programming model and weighted method for analyzed the trade-offs among facility costs, inventory costs, transportation costs, and customer responsiveness for the distribution center locations problem. Farahani and Asgari (2007) implemented a simple set partitioning model to solve a real case about locating the supportive centers in a military logistics systems, where the objectives are minimizing cost of establishing the facilities and improving the quality of all facilities.

Melachrinoudis and Min (2000) formulated a dynamic, multi-objective MIP model for the relocation of manufacturing plants and warehouses problem and solved the model with no-preemptive goal programming method, where the weights for two criteria are equal. Then Min and Melachrinoudis (2005) presented a physical programming formulation to consolidate a warehouse network. Selim and Ozkarahan (2006) determined optimal numbers, locations and capacity levels of facilities and product flows at a minimum cost as well as desired service level for a multi-product and two-stage distribution network system with Fuzzy Multi-objective Programming approach. A genetic algorithm approach is proposed by Altiparmak et al. (2006) for evaluating a greater number of efficient solutions of a multi-criteria optimization supply chain network design problem. Zhou et al. (2003) designed a Bi-objective model to solve the problem of assigning a set of customers to multiple warehouses with minimizing shipping cost and transit time between facilities. A genetic algorithm that is used to find Pareto optimal solutions.

Sabri and Beamon (2000) considered strategic and operational supply chain design simultaneously. The optimal facility network configuration obtained by the strategic sub-model are used as the input of the operational sub-model us to determine material flow through facilities. Multiple performance measures including the cost, fill rate and supply chain flexibility are considered in each sub-model. Du and Evans (2008) applied a bi-objective MIP optimization model to a reverse logistics network design problem. An approach combined scatter search, the dual simplex method and the constraint method is designed to analyze the tradeoffs between minimizing total cost and minimizing total tardiness of cycle time.

Wang et al. (2011) worked on a global level green supply chain network design. A multi-objective MIP model is developed to design the facility locations, product allocation and environment protection level at the minimum total cost and carbon emission over the supply chain. Similarly, Bouzembrak et al. (2011) considered a four stages green supply chain design problem, aiming to select the environment protection technology and transportation mode, and determine the facility configuration and product flows through the supply chain.

Chapter 3

MATHEMATICAL MODEL

3.1 Model Description

The supply chain system considered in this thesis consists of a number of existing production plants at fixed locations, a number of potential distribution center sites and a number of customer zones at fixed locations as well as multiple kinds of fresh products that flow between facilities. Products are shipped from plants to distribution centers, and after that, they are delivered to customer zones to meet the demand, and products cannot be transported from plants to customer zones directly. An assignment problem is considered between distribution center stage and customer zone stage, which means that a distribution center will serve a number of customer zones that are close to it and each customer zone need to be assigned to one and only one distribution center. To solve the supply chain distribution network design problem for fresh produce, a Mixed-integer Programming (MIP) model with three conflicting objectives is formulated.

For the simplification of the model, some reasonable assumptions are made as followings:

(1) The products are shipped to the distribution centers immediately after they have been produced in the production plants and all products reach their peak quality at the time of production.

(2) The products are transported and stored in the same condition after processing and the quality of products degrades linearly over the time until they are shipped to the customers.

(3) The shipments of products between facilities are provided by 3PLs and the transportation rate per unit per mile depends on the shipping point and the type of product.

(4) The invested distribution centers have both upper and lower bounds on their sizes and there are fixed cost and variable cost for operating a distribution center.

(5) The investment cost of distribution centers only depends on the size of the invested distribution centers.

(6) To simply estimate the inventory in each distribution center, regular shipments and delivery schedule is assumed.

(7) A daily shipment from distribution centers to customer zones is considered in this thesis and the lead time should be within one day. So maximum delivery distance between distribution centers and customers zones is taken into account.

(8) Demands in customer zones are assumed to be deterministic and have to be met by the shipments from distribution centers.

3.2 MIP Model

3.2.1 Notation:

Indices:

i: plants' index $i = 1, \dots, I$

j: potential DC sites' index $j = 1, \dots, J$

r: customer zones' index $r = 1, \dots, R$

k: products' index $k = 1, \dots, K$

Parameters:

I: the number of plans

J: the number of potential distribution centers' sites

R: the number of customer zones

K: the number of product types

T_k: planned inventory turns for product k

SL_k: shelf life of product k

p_{ik}: production capacity of product k in plant i

d_{rk}: demand of product k in customer zones r

f_{ij}: distance between plant i and site j

μ_{ij}: delivery lead time from plant i to site j

g_{jr}: distance between site j and customer zone r

c_{ik}^{trans}: transportation cost per mile per unit for product k from plant i

c_{jk}^{trans}: transportation cost per mile per unit for product k from distribution center site j

c_j^{fixed}: fixed operating cost of a distribution center at site j

c_j^{var}: variable operating cost of a distribution center at site j

c_j^{invest}: variable cost for constructing a distribution center at site j

τ_k: the volume of unit product k

α: distribution center capacity factor

π: maximum delivery distance that is allowed between a distribution center and a customer zone

U: maximum size of invested distribution centers

L: minimum size of invested distribution centers

3.2.2 Decision variables

Continuous Variables:

x_{ijk}: the amount of product k shipped from plant i to site j

y_{jrk}: the amount of product k shipped from site j to customer zone r

s_j: the size of the distribution center j

Q_{jk}: centralized demand of product k in distribution center j

Binary Variables:

$$b_j = \begin{cases} 1, & \text{if open a refrigerated distribution center at site } j \\ 0, & \text{otherwise} \end{cases}$$

$$\gamma_{ijk} = \begin{cases} 1, & \text{if product } k \text{ is shipped from plant } i \text{ to distribution center } j \\ 0, & \text{otherwise} \end{cases}$$

$$\theta_{jr} = \begin{cases} 1, & \text{if customer zone } r \text{ is assigned to distribution center } j \\ 0, & \text{otherwise} \end{cases}$$

3.2.3 Model formulation

Objective function:

$$\text{Minimize Total cost } Z_1 = \text{Transportation cost} + \text{Operating cost}$$

$$= \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} f_{ij} * c_{ik}^{trans} * x_{ijk} + \sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{j=1}^{J} g_{jk} * c_{jk}^{trans} * y_{jrk} + \sum_{j=1}^{J} c_j^{fixed} * b_j + \sum_{j=1}^{J} c_j^{var} * s_j \quad (1)$$

Minimize Mean lead time Z_2

$$= \sum_{k=1}^{K} \frac{\sum_{j=1}^{J} \sum_{i=1}^{I} \mu_{ij} * x_{ijk}}{\sum_{r}^{R} d_{rk}} \tag{2}$$

Minimize investment Z_3

$$= c_j^{invest} * \sum_{j=1}^{J} s_j \tag{3}$$

Objective function (1) aims to minimize the total annual cost of supply chain including transportation cost and operating cost of distribution centers. The transportation cost is assumed to be linear to the actual flow of the product from shipping point to the destination. The operating cost for a distribution center consists of fixed cost and variable cost, where variable cost includes labors, utilities, taxes, etc.

For the fresh produce, besides efficiency of the supply chain, the freshness of the product is also a key supply chain performance indicator because it is directly related to the food quality and safety, and also effects the customer service level. In this thesis, the average lead time of product is used to measure the freshness of product due to the assumption of the linear deterioration of the food quality over the time. Objective function (2) aims to minimize the average lead time of the product flow from plants to distribution centers that means improve freshness.

Objective function (3) refers to the investment cost of establishing refrigerated distribution centers. Generally, reducing capital investment is also taken into account for the supply chain design problem. Here, the investment is a linear function of the size of distribution centers.

Opening more distribution centers close to the customer zones can efficiently improve the freshness of product, but it may lead to an increase in transportation cost, operating cost of DCs and investment. So it is necessary for decision makers to balance the three criteria when optimizing the distribution network.

Network structure constraints:

$$\gamma_{ijk} = 0, \qquad \forall (i,j,k) \in \{(i,j,k) | \mu_{ij} \geq SL_k - T_k\} \tag{4}$$

$$\gamma_{ijk} \leq b_j, \qquad \forall i, \forall j, \forall k \tag{5}$$

$$\theta_{jr} = 0, \qquad \forall (j,r) \in \{(j,r) | g_{jr} \geq \pi\} \tag{6}$$

$$\theta_{jr} \leq b_j, \qquad \forall j, \forall r \tag{7}$$

$$\sum_{j=1}^{J} \theta_{jr} = 1, \qquad \forall j, \forall r \tag{8}$$

The first two constraints are defined to satisfy distribution network structure requirements between plants and distribution centers. Constraint (4) means that a link between a production plant and a potential distribution center site may exist only if the lead time plus the inventory time of product does not exceed the shelf life. Constraint (5) ensures that the product can only be shipped to a site that opens a distribution center.

Constraints (6)-(8) are used to ensure the assignment of customer zones to distribution centers. Firstly, a distribution center cannot serve a customer zone if the distance between them exceeds the maximum delivery distance that is allowed. Secondly, customer zone assignments can be made only to a distribution center that has been opened. Furthermore, each customer zone must be assigned to exactly one single distribution center.

Product flow balance constraints:

$$x_{ijk} \leq p_{ik} * \gamma_{ijk}, \qquad \forall i, \forall j, \forall k \tag{9}$$

$$\sum_{j=1}^{J} x_{ijk} \leq p_{ik}, \qquad \forall i, \forall k \tag{10}$$

$$\sum_{i=1}^{I} x_{ijk} = Q_{jk}, \qquad \forall j, \forall k \tag{11}$$

$$\sum_{r=1}^{R} y_{jrk} = Q_{jk}, \qquad \forall j, \forall k \tag{12}$$

$$y_{jrk} = d_{rk} * \theta_{jr}, \qquad \forall j, \forall r, \forall k \tag{13}$$

Constraint (9) implies that the product can be delivered from a production plant to a distribution center only if a link between them exists. Constraint (10) specifies that the sum of shipping quantity from a plant does not exceed the production capacity of that supplier. Constraint (11) guarantees that the centralized demands in a distribution center are met by the sum of the product quantity that comes from all production sites and Constraint (12) corresponds to the centralized demand of product k in distribution center j, which is the sum of product quantity shipped from distribution center j. According to Constraint (13), the shipping quantity of product k between distribution center j and customer zone r equals to the demand in customer zone r if the customer zone r is assigned to the distribution center j. Otherwise, the shipping quantity is set to be zero.

Distribution center capacity constraints:

$$\alpha * \sum_{k=1}^{K} \tau_k \frac{Q_{jk} * T_k * 2}{360} \leq s_j, \qquad \forall j \tag{14}$$

$$s_j \leq U * b_j, \qquad \forall j \tag{15}$$

$$s_j \geq L * b_j, \qquad \forall j \tag{16}$$

Given the specific annual flow of material through the distribution center, the actual space required for a distribution center can be estimated by inventory turns (Simchi-Levi et al., 1999). Assuming a regular shipment and delivery schedule, the required storage space is approximately twice the average inventory level, where the average inventory level equals to the annual throughout divided by the inventory turns. The actual space required can be estimated by multiplying the required storage space by a factor (> 1) because the extra space are need for handling products, processing facilities and others. In this thesis, the factor α is set to three, which is a typical value used in practice. Following the approach, Constraint (14) ensures that the amount of inventory is within the distribution center capacity. Lower and upper bounds on the storage capacity of the invested distribution centers are imposed by Constraints (15)–(16).

Variables constraints:

$$x_{ijk},\ y_{jrk},\ Q_{jk},\ s_j \geq 0, \qquad \forall i, \forall j, \forall r, \forall k \tag{17}$$

$$b_j,\ \gamma_{ijk},\ \theta_{jr} \in (0, 1), \qquad \forall i, \forall j, \forall r, \forall k \tag{18}$$

Nonnegativity of decision variables is defined in Constraints (17) and Constraint (18) restricts the binary variables.

3.3 Solving Approach

3.3.1 General Form MILP

In order to convert the proposed model into a general form Mixed-integer Linear Programming (MILP) model, we introduce a binary variable β_{ijk} and then Constraint (4) can be rewritten as follows:

$$\mu_{ij} - (SL_k - T_k) \leq M * \left(1 - \beta_{ijk}\right), \qquad \forall i, \forall j, \forall k \tag{19}$$

$$\mu_{ij} - (SL_k - T_k) \geq -M * \beta_{ijk}, \qquad \forall i, \forall j, \forall k \tag{20}$$

$$\gamma_{jrk} \leq \beta_{ijk}, \qquad \forall i, \forall j, \forall k \tag{21}$$

Proof: If $\beta_{ijk} = 0$, then we have the following inequalities:

$$\mu_{ij} - (SL_k - T_k) \leq M$$

$$\mu_{ij} - (SL_k - T_k) \geq 0$$

$$\gamma_{jrk} \leq 0$$

Which indicate that γ_{jrk} must equals to zero if $\mu_{ij} \geq SL_k - T_k$.

If $\beta_{ijk} = 1$, then we have:

$$\mu_{ij} - (SL_k - T_k) \leq 0$$

$$\mu_{ij} - (SL_k - T_k) \geq -M$$

$$\gamma_{jrk} \leq 1$$

That implies γ_{jrk} can be one or zero if the lead time μ_{ij} is less than $(SL_k - T_k)$. It is obvious that Constraint (19)-(21) are equivalent to Constraint (4).

With the same way, constraint (6) can be rewritten to the constraint (22)-(24) by introduce a new binary variable δ_{jr}.

$$g_{jr} - \omega \leq M * \left(1 - \delta_{jr}\right), \qquad \forall j, \forall r \tag{22}$$

$$g_{jr} - \omega \leq -M * \delta_{jr}, \qquad \forall j, \forall r \tag{23}$$

$$\theta_{jr} \leq \delta_{jr}, \qquad \forall j, \forall r \tag{24}$$

Binary variable γ_{jrk} and δ_{jr} have no meanings.

3.3.2 Weighted sum method

In this thesis, weighted sum method is used to solve the multi-objective mathematical model which is the simplest approach and widely used classical method for the multi-criteria decision making. It is simple and easy to implement and it guarantees to find solutions on the feasible set for convex problems. The basic idea of this method is to convert the set of objectives into a single objective by multiplying each objective function with an assigned weight. Then the original multi-objective model can be transformed into a single objective model.

To reformulate the model, three weights for the objectives are defined as:

$$w_m \in [0, 1], \qquad \forall m = 1,2,3 \tag{25}$$

$$\sum_{m=1}^{3} w_m = 1 \tag{26}$$

Here, w_m is the weight of the objective function Z_m. It is practical to assume that all the weights are in the range between zero and one and the sum of weights equals to one.

Also, it is essential to scale the objectives for the weighted sum method. In this thesis, the simple scaling method is selected to scale the objective values since it is the most common scaling method used in practice. In simple scaling, the objective values are multiplied by a number to make the values in the same scale. Let c_1, c_2 and c_3 denote the scale number for each objective, then the single objective function can be formulated as followings:

$$\text{Min Z} = \sum_{m=1}^{3} w_m * c_m * Z_m \tag{27}$$

Replacing the objective function (1), (2) and (3) in the original multi-objective Mixed-integer Linear Programing (MILP) model with objective function (27) and introducing weight parameters w_m and scale parameters c_m, the single objective MILP model for the weighted sum method is well constructed.

Chapter 4

NUMRICAL EXAMPLES

4.1 Case Description

In this chapter, a case considering a supply chain network covering 48 states in the US excluding the Hawaii and Alaska is studied to illustrate the approach for designing the optimal distribution network of fresh produce, and to evaluate the profitability of investing the owned refrigerated distribution centers which are used to storing and distributing products. A typical network configuration problem involves large amounts of data including information on the location of customers, retailers, distribution centers and manufacturing facilities and suppliers, the products information, such as volumes, annual demand and associated cost like transportation cost and warehouse cost. For the reason that the amount of data involved in the optimization model is overwhelming, it is necessary to aggregate the data (David Simchi-Levi et al., 1999). Considering the population density and state size, the demand points are aggregated into 202 customer zones (CZs). The detailed distribution of the customer zones is shown in Table 4.1.

To meet the demands of the customer zones, one candidate distribution center is assumed to be located in the central of each state. As mentioned before, one of the main strategic decision that has to be made is the assignment of the customer zones to the distribution centers. The geographical locations of the distribution centers and customer zones are shown in Figure 4.1. The red spots represent the candidate distribution centers' locations and the blue spots represent the center of each customer zones. It is obvious that there are more customer zones in the west and east coast due to larger population density.

Table 4.1. The Number of Customer Zones in Each State

State	# of CZs	State	# of CZs	State	# of CZs	State	# of CZs
AL	4	IA	5	MT	6	RI	1
AZ	2	KS	3	NE	3	SC	4
AR	3	KY	3	NV	2	SD	2
CA	11	LA	7	NM	1	TN	6
CO	3	ME	3	NY	10	TX	17
CT	1	MD	2	NC	5	UT	1
FL	10	MA	2	ND	2	VA	6
GA	6	MI	7	OH	7	WA	3
ID	3	MN	4	OK	3	WV	5
IL	5	MS	6	OR	3	WI	5
IN	6	MO	6	PA	6	WY	2

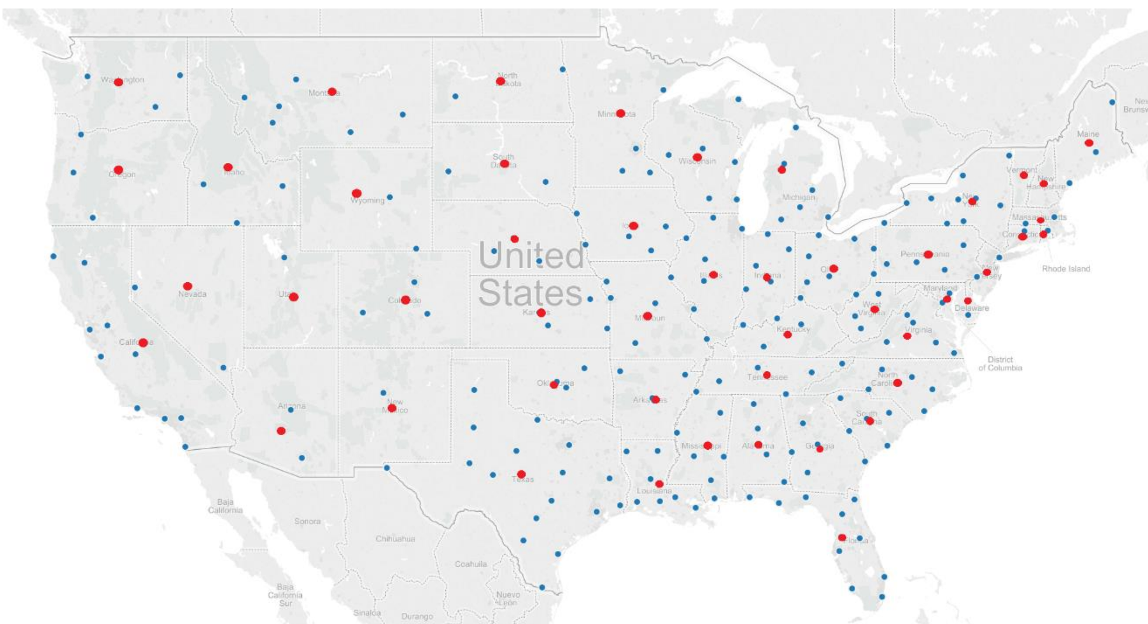

Figure 4.1. Geographical Distribution of DCs and CZs

Generally, the processing sites of fresh produce are close to the growing sites because the products need to be cooled as soon as possible to extend the shelf life. So, it is appropriate to assume that there’s one plant in each state and the production capacity equals to zero of the plants that located in the state have no production of the product. For example, the major strawberry production states include CA, FL, MI, NY, NC, OH, OR, PA, WA and WI, and only the plants located in these 10 states process strawberry. According to the assumption, the production capacity of strawberry in other 38 plants are set to be zero. The fresh produce that considered in this these includes apple and strawberry. The detailed problem settings are illustrated in Table 4.2.

Table 4.2. The Problem Settings

# of plants	I	48
# of potential DCs' sites	J	48
# of customer zones	R	202
# of product types	K	2

4.2 Data Collection

In order to facilitate the analysis, some realistic data needed for the model are collected through various sources. The data includes the regional annual demand at each customer zones, the production at each state, the distance between facilities and the cost incurred throughout the distribution and storing the products. The collection and calculation of the main data are present in the followings.

4.2.1 Demand

The annual demand was derived from the per capita consumption provided by the USDA Economic Research Service (Yearbook tables, 2015). The aggregate level demand at each customer zone is calculated by the multiplication of per capita consumption and the population of the customer zone. Table 4.3 shows the consumption and annual demand information about apple and strawberry.

Table 4.3. Demand Data

	Apple	Strawberry
Per Capita Consumption (Pounds)	16.00	7.81
Total Annual Demand (Pallets)	2494733	2762469

4.2.2 Plant capacity

The plant capacity in a certain state is considered as the amount of production of that state for fresh use. The values of aggregated plant capacity are shown in Table 4-4.

Table 4.4. Production Data

State	Production (Pallets)		State	Production (Pallets)	
	Apple	Strawberry		Apple	Strawberry
Alabama	0	0	Nebraska	0	0
Arizona	561	0	Nevada	0	0
Arkansas	0	0	New Hampshire	5357	0
California	58674	3198727	New Jersey	12245	0
Colorado	6122	0	New Mexico	0	0
Connecticut	7398	0	New York	170918	3704
Delaware	0	0	North Carolina	8163	23495
Florida	0	211458	North Dakota	0	0
Georgia	0	0	Ohio	9082	3241
Idaho	28061	0	Oklahoma	0	0
Illinois	0	0	Oregon	54592	24653
Indiana	1531	0	Pennsylvania	100510	4861
Iowa	0	0	Rhode Island	0	0
Kansas	0	0	South Carolina	0	0
Kentucky	0	0	South Dakota	0	0
Louisiana	0	0	Tennessee	0	0
Maine	11480	0	Texas	0	0
Maryland	8520	0	Utah	6888	0
Massachusetts	11735	0	Vermont	8929	0
Michigan	22959	3819	Virginia	61225	0
Minnesota	0	0	Washington	2729592	11921
Mississippi	0	0	West Virginia	6633	0
Missouri	11225	0	Wisconsin	13520	3588
Montana	0	0	Wyoming	0	0

The production data are all provided by the USDA Economic Research Service (Noncitrus Fruits and Nuts 2014 summary, 2015). There are 10 major production states for strawberry and 24 for apple. So there are 38 plants have zero production capacity for strawberry and 24 plants have no production of apple.

4.2.3 Transportation cost

Reefer rates refer to the transportation cost of refrigerated trucks and are reported by the DAT Solutions. The reefer rates of five areas are different and values shown in below Table 4.5.

Table 4.5. Reefer Rates

Area	Reefer rates ($/Truckload/mile)	States
West	2.02	AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA, WY
Midwest	2.28	IL, IN, IA, KS, MI, MN, MO, NE, ND, OH, SD, WI
South Central	1.89	AR, LA, OK, TX
Southeast	1.83	AL, FL, GA, KY, MS, NC, SC, TN, VA, WV
Northeast	1.47	CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT

The refrigerated truck with standard 48' reefer trailer is taken into account in this thesis. The weight and volume capacity and the corresponding pallet capacity for apple and strawberry are calculated by the minimum number of the value of weight capacity divided by a single pallet weight and the value of volume capacity divided by the volume size of a pallet. The results of truck capacity are shown in Table 4.6. Then the transportation cost per unit per mile can be calculated by dividing the reefer rate by the pallet capacity.

Table 4.6. Refrigerated Truck Capacity

Weight Capacity (pounds)	Volume Capacity (cubic feet)	Apple Capacity (pallet)	Strawberry Capacity (pallet)
40000	3700	20	30

4.3 Solutions

To provide the solution of the problem, the MILP model Goal Programming model are solved in ILOG CPLEX Optimization Studio. All the experiments are run on a PC with Intel Core i7-3770s and 16 GB RAM. The corresponding CPLEX code for solving the problem are attached in Appendix A.

4.3.1 Ideal value

We first solve the optimization model under the objective function (1) and obtain the minimum annual cost and associated mean lead time and investment cost. The model are solved under three scenarios, single product of apple, single product of strawberry and multiple products of apple and strawberry. The detailed results are shown in Table 4.7.

Table 4.7. Ideal Value for Annual Supply Chain Cost

	Apple	Strawberry	Apple & Strawberry
Annual Cost ($Billions)	4.115	3.358	7.549
Mean Lead Time (Days)	2.738	3.101	3.034
Total size of DCs (10^7Cubic feet)	1.808	0.518	2.270
Investment ($Billions)	1.229	0.352	1.544

Then the minimum average lead time for products can be obtained by solving the model with objective function (2). The results are shown in Table 4.8.

Table 4.8. Ideal Value for Mean Lead Time

	Apple	Strawberry	Apple & Strawberry
Mean Lead Time (Days)	2.615	2.964	2.785

The results of running the model under objective function (3), minimizing investment cost, are provided in Table 4.9. The corresponding annual supply chain cost and the mean lead time is also provided.

Table 4.9. Ideal Value for Investment

	Apple	Strawberry	Apple & Strawberry
Investment ($Billions)	1.221	0.316	1.537
Total size of DCs (10^7Cubic feet)	1.796	0.464	2.260
Annual Cost ($Billions)	5.917	4.407	9.832
Mean Lead Time (Days)	3.895	3.873	3.698

4.3.2 Weighted sum method

Although the weighted sum method is simple, it involves the non-simple question: what value of the weights should be assigned? Usually, the weights are designed by the relative importance of each objective. In this thesis, seven different combinations of weights are selected to solve the problem, which are given in Table 4.10. The first three combinations generate solutions with most of the weight given to annual cost, average lead time and investment cost, respectively and the last three combinations generate solutions with moderately more weight given to each objective. The combination 4 gives the solution with equal weights.

Table 4.10. Combination of Weights

Combination	w_1	w_2	w_3
1	4/5	1/10	1/10
2	1/10	4/5	1/10
3	1/10	1/10	4/5
4	1/3	1/3	1/3
5	1/2	1/3	1/6
6	1/6	1/2	1/3
7	1/3	1/6	1/2

The implementation of weighted sum method for the multi-objective is illustrated under the multi-product scenario. Base on the ideal objective value we obtained, we select $(c_1, c_2, c_3) = (7e^{-8}, 0.5,\ e^{-8})$ as the scale number. By multiplying the scale numbers, the objective values all fall into the range 1 to 2, which means they are in the same scale. Then the normalized weighted objective function is given as:

$$\text{Min Z} = w_1 * 7e^{-8} * Z_1 + w_1 * 0.5 * Z_2 + w_2 * e^{-8} * Z_1$$

With assigning different combinations of weights in the objective function and running the model, seven efficient solutions are generated, which are given in Table 4.11.

Table 4.11. Weighted Sum Method Objective Values

(w_1, w_2, w_3)	Annual Cost ($Billions)	Mean Lead Time (Days)	Investment ($Billions)	# of DCs
(4/5, 1/10, 1/10)	7.595	2.951	1.537	34
(1/10, 4/5, 1/10)	8.066	2.809	1.555	27
(1/10, 1/10, 4/5)	7.764	2.823	1.541	34
(1/3, 1/3, 1/3)	8.050	2.890	1.538	28
(1/2, 1/3, 1/6)	8.095	2.991	1.540	24
(1/6, 1/2, 1/3)	7.955	2.825	1.560	32
(1/3, 1/6, 1/2)	8.156	2.951	1.537	18

Figure 4.2. shows the variations in the total annual supply chain cost with different weight combinations of the three objectives. It can be observed that the annual supply chain achieves the lowest value when assigned the heavy weight to it. However, the annual cost may either increase or decrease with the increasing weights assigned to the annual cost. When the weight changes from 1/6 to 1/3, the annual cost increases obviously and even achieved highest among all the solutions. And when the weight assigned to the annual cost equals to 1/10, the values obtained for changing weights of other objectives have a large difference. The reason for why such situation happened may because of the effect of other criteria on the annual cost.

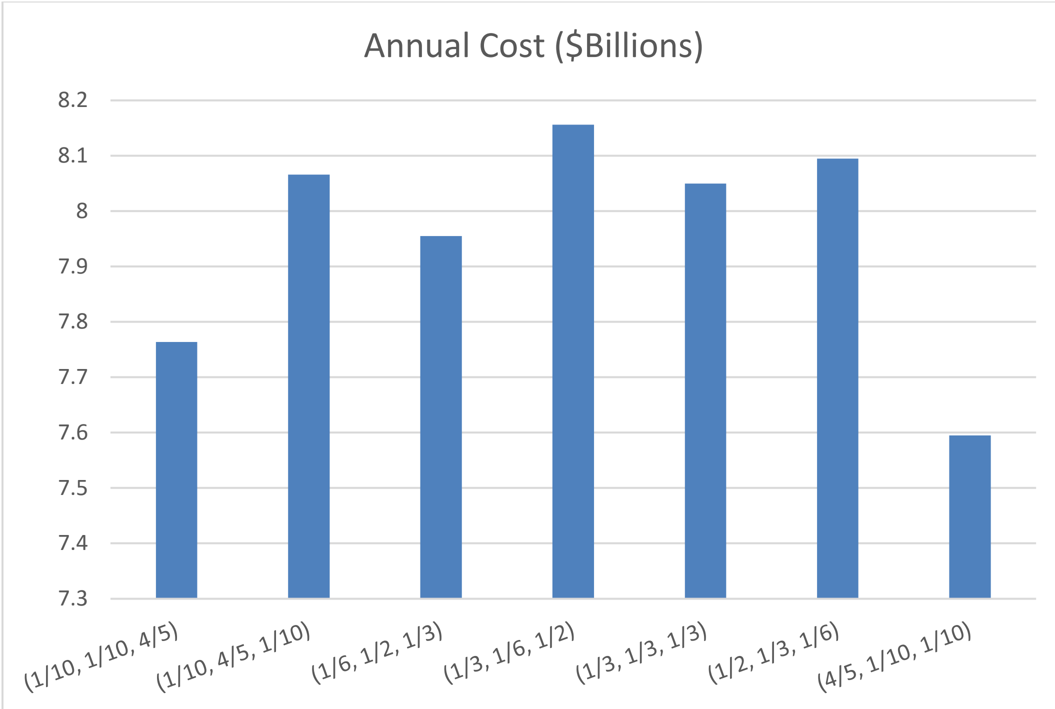

Figure 4.2. Variation in Annual Supply Chain Cost with Different Weights

By observing Figure 4.3, we can see that the average lead time is lowest when 4/5 is put in the second objective. But it increases when the assigned weight on this objective increases from 1/10 to 1/6 and then decrease obviously when the weight change from 1/6 to 1/3. That may implies that putting relatively more weights on both annual cost and investment will lead to a considerable increasing in average lead time.

Figure 4.4. illustrates the variation in investment cost when changing the assigned weights on the objective of minimizing investment cost. The values of investment cost are close except for the values obtained by weight combination (1/10, 4/5, 1/10) and (1/6, 1/2, 1/3). But the lowest value of the investment is achieved when a heavy weight is put in the annual cost. The tradeoff among the three criteria is studied in the next section.

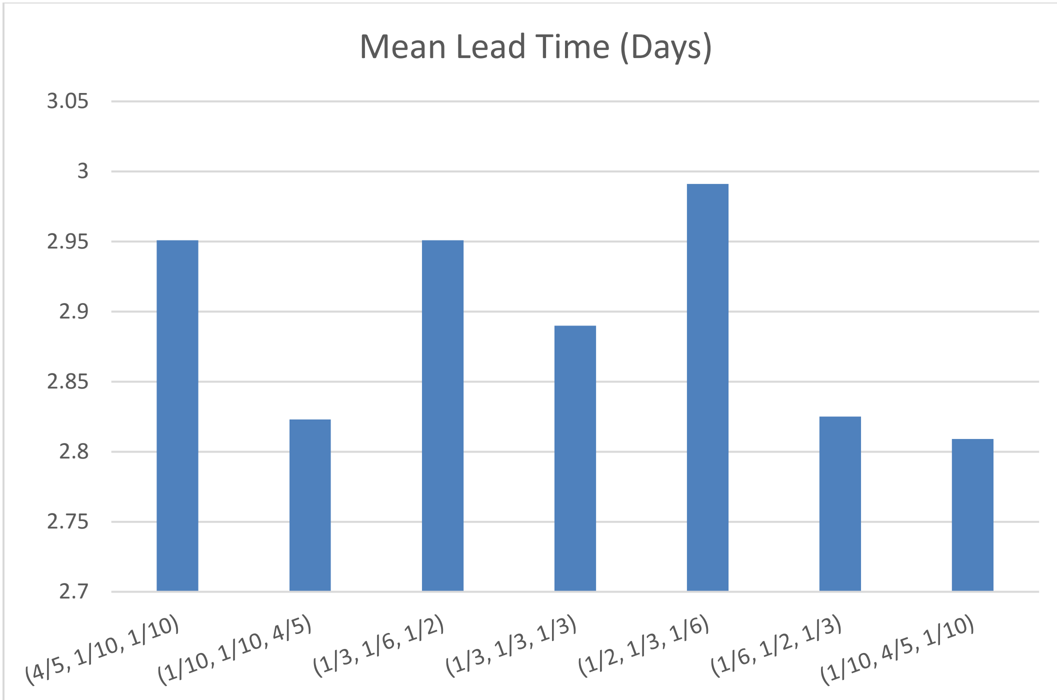

Figure 4.3. Variation in Mean Lead Time with Different Weights

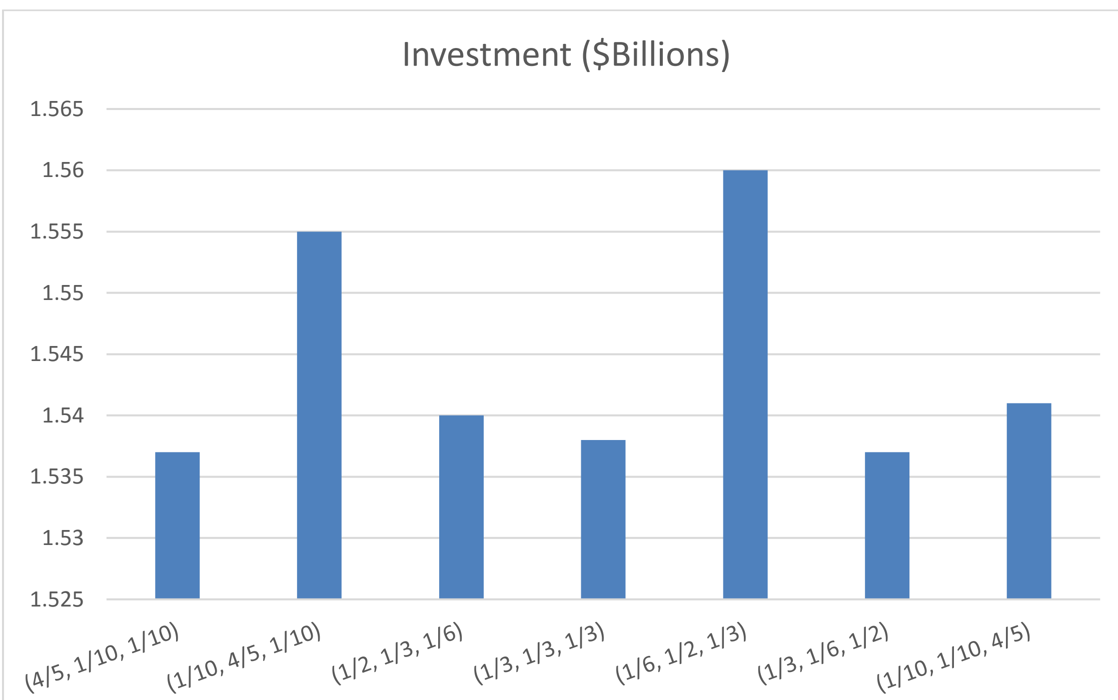

Figure 4.4. Variation in Investment with Different Weights

Chapter 5

RESULTS ANALYSIS

5.1 Trade-offs among Criteria

To compare the solutions generated by the seven combinations of weights, all the objective values are expressed as the ratio of their ideal values. That is, the objective function values are divided by the ideal values. The resulted percentage values are shown in Table 5.1.

Table 5.1. Percentage of Ideal Value for Objectives

	Percentage of ideal value		
(w_1, w_2, w_3)	Annual Cost	Mean Lead Time	Investment
(4/5, 1/10, 1/10)	100.61%	105.96%	100.00%
(1/10, 4/5, 1/10)	106.85%	100.86%	101.17%
(1/10, 1/10, 4/5)	102.85%	101.36%	100.26%
(1/3, 1/3, 1/3)	106.64%	103.77%	100.07%
(1/2, 1/3, 1/6)	107.23%	107.40%	100.20%
(1/6, 1/2, 1/3)	105.38%	101.44%	101.50%
(1/3, 1/6, 1/2)	108.04%	105.96%	100.00%

The values in the table show that the impact of different weights on the investment cost is relatively low and the combination (4/5, 1/10, 1/10) generate the efficient solution with the ideal value for investment cost and lowest increase in the annual cost. However, the corresponding average lead time increased approximately 6%, which is relatively higher than the other combinations of weights. The weight combination (1/3, 1/6, 1/2) also gives the lowest investment cost, but the associated annual cost is the highest. When the average lead time reaches the best value of all combinations, the associated investment cost is higher than others.

In order to support the Decision Maker (DM) to choose a solution from the different solutions generated by the Weighted Sum Method, the Value Path Approach (VPA) (Schilling et al, 1983) is used to graphically display the trade-offs among objective function values under different assigned weights. VPA is effective for determining dominated and non-dominated solutions. If the value paths of two solutions do not intersect, then one path must lie above another and the associated solution is dominated for the minimization problem. If two value paths cross each other, then the corresponding solutions do not dominate each other. The graph for Value Path Approach (VPA) is shown in Figure 5.1.

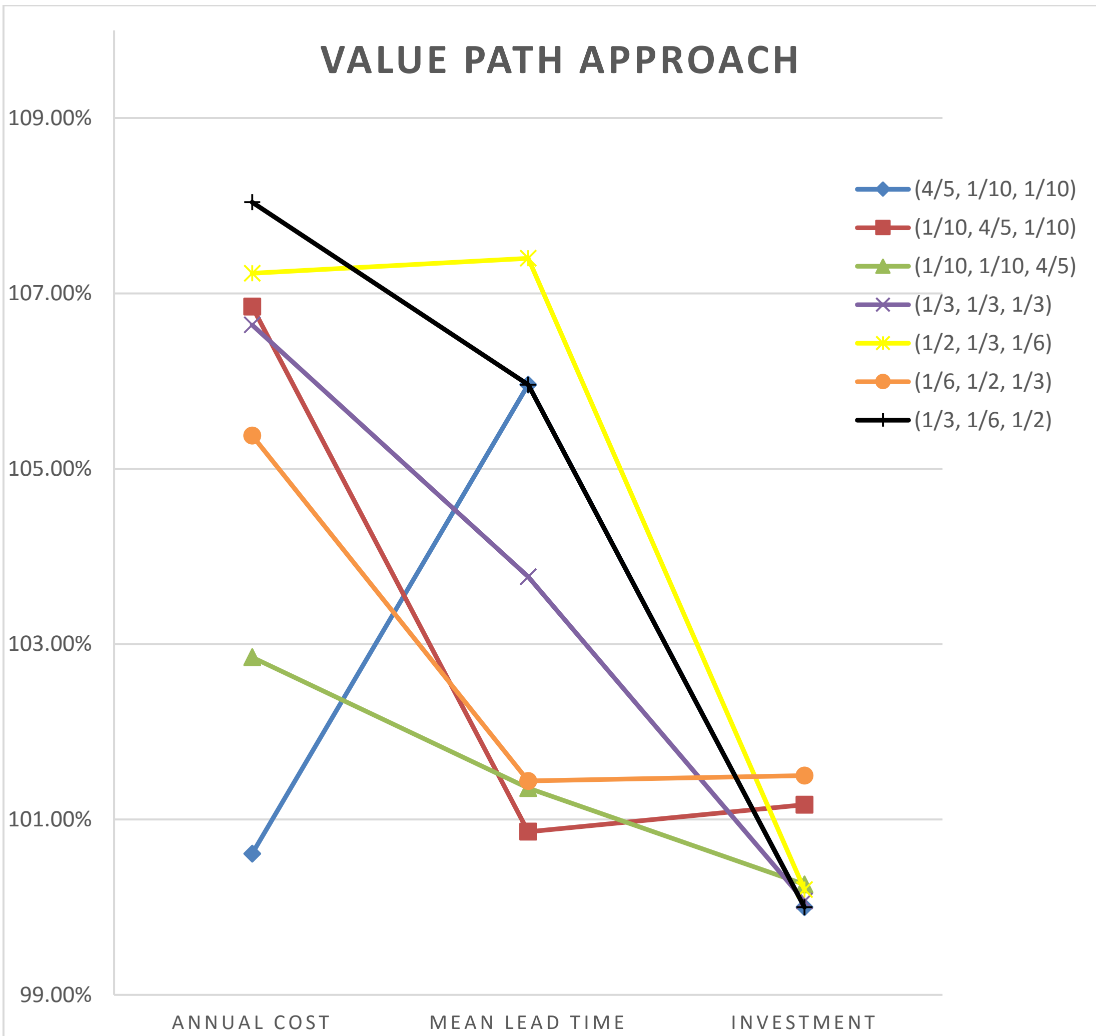

Figure 5.1. Value Path Comparison for Supply Chain Design Solution

It is observed that the yellow line for weight combination (1/2, 1/3, 1/6) is above the blue line for weight combination (4/5, 1/10, 1/10) and the purple line for weight combination (1/3, 1/3, 1/3), which means that the solution obtained by assigning weights (1/2, 1/3, 1/6) on the objectives dominates the other two solutions. Also the orange line is entirely above the green line, which means that the solution generated by weight combination (1/10, 1/10, 4/5) is dominated by the solution generated by weight combination (1/6, 1/2, 1/3). The other five solutions are all non-dominated since their value paths intersect with each other.

Also, VPA shows that the three criteria are conflicting, especially average lead time and investment, which can be identified by considering weight combination (1/10, 4/5, 1/10) and (1/3, 1/6, 1/2). The first associated solution is 5.07% better than the second one in average lead time, but generates 1.17% higher investment cost. Due to we only considered the variable cost for investing distribution centers, the investment cost is mainly effected by the demand which is assumed to be deterministic and hence the changes in investment cost is slight by assigning different weights. However, the annual cost is more sensitive to the assigned weights. The value of the percentage of ideal value for annual cost ranges from 100.61% to 108.04%.

5.2 Supply Chain Distribution Network

The solution with lowest annual cost and investment cost that is generated by the weight combination (4/5, 1/10, 1/10) is selected to analyze the supply chain distribution network.

5.2.1 The size and location of DCs

The efficient solution about the location and size of distribution centers and the number of served customer zones as well as the total served population are illustrated in Table 5.2.

Table 5.2. Supply Chain Network Solution under Weights (4/5, 1/10, 1/10)

State	Size of DC	Percentage of Total Size	Cumulative Percentage	# of assigned CZs	Total Population
CA	2712800	12.00%	12.00%	9	36678891
TN	1901300	8.41%	20.41%	16	25706431
TX	1885800	8.34%	28.76%	16	25497201
PA	1709800	7.56%	36.32%	3	23117971
IA	1538600	6.81%	43.13%	16	20802066
FL	1144600	5.06%	48.19%	5	15475160
IN	1111300	4.92%	53.11%	10	15026010
WI	731690	3.24%	56.35%	7	9892786
NJ	625200	2.77%	59.11%	2	8453094
MD	618420	2.74%	61.85%	2	8361343
MA	565080	2.50%	64.35%	2	7640119
UT	536720	2.37%	66.72%	4	7256735
NY	536320	2.37%	69.10%	9	7251371
WA	525940	2.33%	71.42%	6	7111006
AZ	497840	2.20%	73.62%	2	6731000
OR	491060	2.17%	75.80%	8	6639434
OK	488140	2.16%	77.96%	8	6599963
KS	484000	2.14%	80.10%	6	6543931
OH	481290	2.13%	82.23%	4	6507240
SD	463100	2.05%	84.28%	5	6261357
NE	460350	2.04%	86.31%	8	6224122
NC	446960	1.98%	88.29%	4	6043079
NV	427790	1.89%	90.18%	3	5783929
NM	399800	1.77%	91.95%	9	5405442
MS	382760	1.69%	93.65%	10	5175185
AR	282430	1.25%	94.89%	3	3818555
KY	236200	1.04%	95.94%	5	3193610
CT	187780	0.83%	96.77%	1	2538840
LA	150380	0.67%	97.44%	2	2033209
SC	134070	0.59%	98.03%	2	1812746
MI	131860	0.58%	98.61%	2	1782786
ND	107030	0.47%	99.09%	3	1447066
NH	104230	0.46%	99.55%	3	1409234
MT	102360	0.45%	100.00%	7	1383923

As shown in the table, total 34 distribution centers are established. Among them, the size of distribution center in California contributes to 12% of total invested size of distribution centers. And the cumulative size of the first 18 distribution centers is more than 80% of the total size, which means the approximately a half number of distribution centers service 80% percent of demand. The top ten largest distribution center located in CA, TN, TX, PA, IA, FL, IN, WI, NJ and MD. The research about the refrigerated warehouse capacity provided by the United State Department of Agriculture (January 2016) shows the similar summary. California has 13.67% refrigerated storage capacity of the total storage capacity in the United States, and the total storage capacity of the first 18 states is 80% of the total capacity in the US. The top ten largest refrigerated storage capacity states are CA, FL, TX, GA, PA, WI, WA, IL, NJ and OR, and six of them also fall in the top ten distribution center locations of the results of our problem. The detailed research data are provided in Table 5.3.

By comparing to the production data of each state, we can see the relevance between the production and the size and location of DCs. The California and Florida are the major production states of strawberry, and New York, Washington and Pennsylvania are the major production states of apples and the sizes of DCs in these states are comparatively larger. The distribution centers are more likely to be located in the states with higher population density. However, there are few DCs located in states with small population, like MT, NH and ND, which may be caused by the limitation on the delivery distance between DCs and CZs. Also, the other factors that are not considered in the model may also have a significant effect on the decision making. For example, locating a distribution center near the interstate high ways may result in a more efficient delivery response time, establishing distribution centers in more rural, high-unemployment areas may achieve a lower operation cost and the environment of the locations may also has an impact on the efficiency of the operation. So, it may need the decision maker to consider more factor to make the final decision.

Table 5.3. Refrigerated Storage Capacity Data Provided by USDA

State	Storage Capacity	Percentage of Total Capacity	Cumulative Percentage	State	Storage Capacity	Percentage of Total Capacity	Cumulative Percentage
CA	569,936	13.67%	13.67%	NE	54,247	1.30%	89.80%
FL	285,598	6.85%	20.52%	KS	47,560	1.14%	90.94%
TX	252,709	6.06%	26.58%	UT	46,530	1.12%	92.05%
GA	250,205	6.00%	32.59%	MD	39,528	0.95%	93.00%
PA	241,945	5.80%	38.39%	AL	36,539	0.88%	93.88%
WI	221,687	5.32%	43.71%	DE	30,249	0.73%	94.60%
WA	211,209	5.07%	48.77%	CO	28,251	0.68%	95.28%
IL	200,294	4.80%	53.58%	SC	27,738	0.67%	95.95%
NJ	167,522	4.02%	57.60%	KY	24,404	0.59%	96.53%
OR	134,369	3.22%	60.82%	AZ	18,742	0.45%	96.98%
IN	113,995	2.73%	63.55%	LA	15,684	0.38%	97.36%
MO	112,098	2.69%	66.24%	MS	15,630	0.37%	97.73%
NY	102,689	2.46%	68.70%	OK	14,498	0.35%	98.08%
MI	101,898	2.44%	71.15%	SD	11,673	0.28%	98.36%
MA	95,028	2.28%	73.43%	NH	10,552	0.25%	98.61%
MN	93,563	2.24%	75.67%	ND	10,325	0.25%	98.86%
AR	92,854	2.23%	77.90%	ME	9,729	0.23%	99.10%
IA	91,249	2.19%	80.09%	CT	6,018	0.14%	99.24%
OH	79,581	1.91%	82.00%	NM	5,336	0.13%	99.37%
VA	78,406	1.88%	83.88%	VT	3,683	0.09%	99.46%
TN	67,732	1.62%	85.50%	AK	3,645	0.09%	99.54%
NC	64,032	1.54%	87.04%	MT	1,231	0.03%	99.57%
ID	60,728	1.46%	88.50%				

5.2.2 Assignment of CZs to DCs

Table 5.2. also shows the assignment results. It can be observed some of distribution centers only delivery product to one or two customer zones, such as the DC in Connecticut and Louisiana, and some of distribution centers operated under a size close to the lower bound. Although we have assumed the operating cost of distribution center is a linear function of the

size, the actual unit operating cost is decreasing by the increase on the size in practice. To improve the utilization of storage capacity and reduce the operating cost, it is appropriate to consolidate the distribution centers with small size to the closed larger distribution centers. Supply chain consolidation is common used in the real case since usually it can reduce the capital investment cost, is effective in reducing inventory cost. However, such consolidation may cause increasing in the response time from distribution centers to customer zone. In a result, the choice of consolidation strategy needs more analysis and consideration.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

A supply chain distribution network design problem encountered in multi-criteria, multi-stage, multi-product, and single-period contexts is studied in this thesis. The problem is formulated as a Mixed-integer Linear Programming (MILP) model with three minimization objectives, including total annual cost, average lead time and investment cost. The developed model intends to determine the optimal numbers, locations and capacity of distribution center and the assignment of customer zones to the distribution centers that can meet all the demand. Weighted sum method is selected to solve the model and analyze the trade-offs among criteria.

A case study about the domestic distribution network of fresh apple and strawberry is given to illustrate the application of the model and method. Firstly, the model is solved by running it with each objective separately to get the ideal values of the objective functions. Then seven weight combinations are assigned to three objectives to generate efficient solutions for the problem with Weighted Sun Method. Finally, the analysis of trade-offs among multiple criteria and designed supply chain distribution network are conducted.

There are total seven solutions generated and two of them are dominated. The trade-offs among three objectives are displayed by the Value Path Approach. The effect of changing different weights on the annual cost and average lead time is obvious, whereas the effect on the investment cost is relatively slight. There are many other efficient solutions that are not generated in this study, and other factors may impact the final decisions. Generally, the solutions provided by the model is used to support the decision making. Further consideration and analysis may be needed for decision maker to determine the final decision.

6.2 Future Research

There are some possible future research can be considered:

- The model can be extended to incorporate the uncertain demand. The uncertainty can be considered as a distribution or several discrete scenarios.
- The decisions made in this work based on a single period planning. However, multi-period model can be formulated to solve the problem with longer planning horizon, like 5 years or 10 years.
- Tactical supply chain planning can be considered at the same time. The solution for the strategic planning can be used as the input of the tactical planning problem and the output of the tactical planning can help to adjust the strategic decisions.

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Appendix

CPLEX CODE

CPLEX Code for Ideal Values of Single Product:

```
//settings
int State = ...;
int CustomerZone = ...;

range I = 1..State;
range J = 1..State;
range K = 1..CustomerZone;

//parameters
float f[I][J] = ...; //distance
float g[J][K] = ...; //distance
float u[I][J] = ...; //LeadTime
float c_trans[J] = ...; //transportation cost/mile/truck
float w = ...; //maximum shipping distance between DC and Retailers
float c_fixed = ...; //fixed operating cost
float c_var = ...; //variable operating cost
float M = ...; //a large number
float c_invest = ...;
float U = ...; //upper bound of DC size
float L = ...; //lower bound of DC size
float a = ...;    //distribution center capacity factor

//Product info
float p[I] = ...; //production capacity
float d[K] = ...; //demand
float SL = ...; //shelf-life
float ratio = ...; //ratio inventory turns to shelf life [0,1]
float PalletSize = ...;
float n = ...; //units per truck

//decision variables
dvar boolean b[J];
dvar boolean theta[J][K];
dvar boolean darta[J][K];
dvar boolean gama[I][J];
dvar boolean beta[I][J];
dvar float+ x[I][J];
dvar float+ y[J][K];
dvar float+ v[J];
dvar float+ Q[J];
dvar float+ SUMQ;
dvar float+ MeanLeadtime;
dvar float+ AnnualCost;
dvar float+ Investment;

//objectives
```

```
minimize
  AnnualCost;
  //MeanLeadtime;
  //Investment;

//constraints
subject to {
//Annual Cost equation
  sum (i in I, j in J) f[i][j] * x[i][j] * c_trans[i] / n +
  sum (j in J, k in K) y[j][k] * g[j][k] * c_trans[j] / n +
  sum (i in J) c_fixed * b[i] + sum (i in J) (c_var)* v[i] ==
AnnualCost;

//Mean Leadtime equation
  (sum (i in I, j in J) u[i][j] * x[i][j] )
  /sum (k in K) d[k] == MeanLeadtime;

//Investment equation
  sum(j in J) v[j] * c_invest == Investment;

ctNetworkStructureIJ:
      forall (i in I, j in J)
        u[i][j] - (1-ratio) * SL <= M * (1 - beta[i][j]);
      forall (i in I, j in J)
        u[i][j] - (1-ratio) * SL >= -M * beta[i][j];
      forall (i in I, j in J)
        gama[i][j] <= beta[i][j];
      forall (i in I, j in J)
        gama[i][j] <= b[j];

      forall (j in J, k in K)
        g[j][k] - w <= M * (1 - darta[j][k]);
      forall (j in J, k in K)
        -M * darta[j][k] <= g[j][k] - w;
      forall (j in J, k in K)
        theta[j][k] <= darta[j][k];
      forall (j in J, k in K)
        theta[j][k] <= b[j];
      forall (k in K)
        sum (j in J) theta[j][k] == 1;

ctProductFlow:
      forall (i in I, j in J)
        x[i][j] <= p[i] * gama[i][j];
      forall (i in I)
        sum (j in J) x[i][j] <= p[i];
      forall (j in J, k in K)
        y[j][k] == d[k] * theta[j][k];
      forall (j in J)
        sum (k in K) y[j][k] == Q[j];
      forall (j in J)
        sum (i in I) x[i][j] >= Q[j];

ctStorageCapacity:
      forall (j in J)
        Q[j] * SL * ratio * 2 * PalletSize * a / 360 <= v[j];
      forall (j in J)
```

```
        v[j] <= U * b[j];
      forall (j in J)
        v[j] >= L * b[j];

sum(j in J) v[j] == SUMQ;
}
```

CPLEX Code for Ideal Values of Multi-products:

```
//parameters
int State = ...;
int CustomerZone = ...;
int Product = ...;

range S = 1..State;
range R = 1..CustomerZone;
range K = 1..Product;


float f[S][S] = ...; //distance between plants and DCs
float g[S][R] = ...; //distance between DCs and CZs
float u[S][S] = ...; //leadTime from plants to DCs
float c_trans[S] = ...; //transportation cost/mile/truck
float c_fixed = ...; //fixed operating cost
float c_invest = ...;
float c_var = ...; //variable operating cost
float M = ...; //a large number
float w = ...; //maximum shiping distance
float U = ...; //upper bound of DC size
float L = ...; //lower bound of DC size
float a = ...;    //distribution center capacity factor


float p[K][S] = ...; // production capacity
float d[K][R] = ...; // demand
float SL[K] = ...; // shelf life
float n[K] = ...; //number of pallet per truckload
float PalletSize[K] = ...;
float ratio[K] = ...; //ratio of inventory turns to shelf life [0,1]

//decision variables
dvar boolean gama[K][S][S];
dvar boolean beta[K][S][S];
dvar boolean b[S]; //binary variable for openning DCs
dvar float+ x[K][S][S]; //shipping quantity from plant to DC
dvar float+ y[K][S][R]; //shipping quantity from DC to CZ
dvar float+ v[S]; //size of DC
dvar float+ Q[K][S]; // centralized demand
dvar boolean theta[S][R];
dvar boolean darta[S][R];
dvar float+ SUMQ;
dvar float+ MeanLeadtime;
dvar float+ AnnualCost;
dvar float+ Investment;
```

```
//objectives
minimize
  AnnualCost;
  //MeanLeadtime;
  //Investment;

subject to {

//Annual Cost equation
sum (i in S, j in S, k in K) f[i][j] * x[k][i][j] * c_trans[i]/ n[k] +
sum (j in S, r in R, k in K) y[k][j][r] * g[j][r] * c_trans[j]/ n[k] +
sum (i in S) c_fixed * b[i] + sum (i in S) c_var * v[i] == AnnualCost;

//Mean Leadtime equation
(sum (i in S, j in S, k in K) u[i][j] * x[k][i][j])/
sum (k in K, r in R) d[k][r] == MeanLeadtime;

//Investment equation
sum(j in S) c_invest * v[j] == Investment;

//Network structure constraints
      forall (i in S, j in S, k in K)
        u[i][j] - (1-ratio[k]) * SL[k] <= M * (1 - beta[k][i][j]);
      forall (i in S, j in S, k in K)
        u[i][j] - (1-ratio[k]) * SL[k] >= -M * beta[k][i][j];
      forall (i in S, j in S, k in K)
        gama[k][i][j] <= beta[k][i][j];
      forall (i in S, j in S, k in K)
        gama[k][i][j] <= b[j];

      forall (j in S, r in R)
        g[j][r] - w <= M * (1 - darta[j][r]);
      forall (j in S, r in R)
        (0-M) * darta[j][r] <= g[j][r] - w;
      forall (j in S, r in R)
        theta[j][r] <= darta[j][r];
      forall (j in S, r in R)
        theta[j][r] <= b[j];
      forall (r in R)
        sum (j in S) theta[j][r] == 1;

//Product flow constraints
      forall (i in S, j in S, k in K)
        x[k][i][j] <= p[k][i] * gama[k][i][j];
      forall (i in S, k in K)
        sum (j in S) x[k][i][j] <= p[k][i];
      forall (j in S, k in K)
        sum (i in S) x[k][i][j] == Q[k][j];
      forall (j in S, k in K)
        sum (r in R) y[k][j][r] == Q[k][j];
      forall (j in S, r in R, k in K)
        y[k][j][r] == d[k][r] * theta[j][r];

//Storage Capacity constraints:
      forall (j in S)
        sum (k in K) Q[k][j] * PalletSize[k] * SL[k] *
```

```
        ratio[k] * 2 * a / 360 <= v[j];
      forall (j in S)
        v[j] <= U * b[j];
      forall (j in S)
        v[j] >= L * b[j];

//Total size of DC
sum(j in S) v[j] == SUMQ;
}
```

CPLEX Code for Weighted Sum Method:

```
//parameters
int State = ...;
int CustomerZone = ...;
int Product = ...;

range S = 1..State;
range R = 1..CustomerZone;
range K = 1..Product;
range O = 1..3;


float f[S][S] = ...; //distance between plants and DCs
float g[S][R] = ...; //distance between DCs and CZs
float u[S][S] = ...; //leadTime from plants to DCs
float c_trans[S] = ...; //transportation cost/mile/truck
float c_fixed = ...; //fixed operating cost
float c_invest = ...;
float c_var = ...; //variable operating cost
float M = ...; //a large number
float w = ...; //maximum shiping distance
float U = ...; //upper bound of DC size
float L = ...; //lower bound of DC size
float a = ...;    //distribution center capacity factor


float p[K][S] = ...; // production capacity
float d[K][R] = ...; // demand
float SL[K] = ...; // shelf life
float n[K] = ...; //number of pallet per truckload
float PalletSize[K] = ...;
float ratio[K] = ...; //ratio of inventory turns to shelf life [0,1]

float pai[O] = [4/5, 1/10, 1/10]; //weights


//decision variables
dvar boolean gama[K][S][S];
dvar boolean beta[K][S][S];
dvar boolean b[S]; //binary variable for openning DCs
dvar float+ x[K][S][S]; //shipping quantity from plant to DC
dvar float+ y[K][S][R]; //shipping quantity from DC to CZ
dvar float+ v[S]; //size of DC
```

```
dvar float+ Q[K][S]; // centralized demand
dvar boolean theta[S][R];
dvar boolean darta[S][R];
dvar float+ SUMQ;
dvar float+ MeanLeadtime;
dvar float+ AnnualCost;
dvar float+ Investment;

//weighted objectives
minimize
  pai[1] * AnnualCost / 700000000 +
  pai[2] * MeanLeadtime / 2 +
  pai[3] * Investment / 100000000;

subject to {

//Annual Cost equation
sum (i in S, j in S, k in K) f[i][j] * x[k][i][j] * c_trans[i]/ n[k] +
sum (j in S, r in R, k in K) y[k][j][r] * g[j][r] * c_trans[j]/ n[k] +
sum (i in S) c_fixed * b[i] + sum (i in S) c_var * v[i] == AnnualCost;

//Mean Leadtime equation
(sum (i in S, j in S, k in K) u[i][j] * x[k][i][j])/
sum (k in K, r in R) d[k][r] == MeanLeadtime;

//Investment equation
sum(j in S) c_invest * v[j] == Investment;

//Network structure constraints
      forall (i in S, j in S, k in K)
        u[i][j] - (1-ratio[k]) * SL[k] <= M * (1 - beta[k][i][j]);
      forall (i in S, j in S, k in K)
        u[i][j] - (1-ratio[k]) * SL[k] >= -M * beta[k][i][j];
      forall (i in S, j in S, k in K)
        gama[k][i][j] <= beta[k][i][j];
      forall (i in S, j in S, k in K)
        gama[k][i][j] <= b[j];

      forall (j in S, r in R)
        g[j][r] - w <= M * (1 - darta[j][r]);
      forall (j in S, r in R)
        (0-M) * darta[j][r] <= g[j][r] - w;
      forall (j in S, r in R)
        theta[j][r] <= darta[j][r];
      forall (j in S, r in R)
        theta[j][r] <= b[j];
      forall (r in R)
        sum (j in S) theta[j][r] == 1;

//Product flow constraints
      forall (i in S, j in S, k in K)
        x[k][i][j] <= p[k][i] * gama[k][i][j];
      forall (i in S, k in K)
        sum (j in S) x[k][i][j] <= p[k][i];
      forall (j in S, k in K)
        sum (i in S) x[k][i][j] == Q[k][j];
      forall (j in S, k in K)
```

```
        sum (r in R) y[k][j][r] == Q[k][j];
      forall (j in S, r in R, k in K)
        y[k][j][r] == d[k][r] * theta[j][r];

//Storage Capacity constraints:
      forall (j in S)
        sum (k in K) Q[k][j] * PalletSize[k] * SL[k] *
        ratio[k] * 2 * a / 360 <= v[j];
      forall (j in S)
        v[j] <= U * b[j];
      forall (j in S)
        v[j] >= L * b[j];

//Total size of DC
sum(j in S) v[j] == SUMQ;
}
```