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The Intermodal Freight Transportation Institute (IFTI)
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OPTIMAL PACKAGING OF HIGH VALUE, TEMPERTURE SENSITIVE, PERISHABLE PRODUCTS

DRAFT FINAL REPORT

Prepared By:

Mohammed Yeasin, Ph.D.

Associate Professor, Department of Electrical and Computer Engineering, The University of Memphis, 3815 Central Avenue, Memphis, TN 38152, Email: myeasin@memphis.edu

Sabya Mishra, Ph.D., P.E.
Assistant Professor, Dept. of Civil Engineering, University of Memphis, 112D Engr. Sc. Bldg., 3815 Central Avenue, Memphis, TN 38152, Tel: 901-678-5043, Fax: 901-678-3026, Email: smishra3@memphis.edu

Mohsen Maniat
Department of Civil Engineering, The University of Memphis, 3815 Central Avenue, Memphis, TN 38152, Phone: (901) 612-7898, Email: mmaniat@memphis.edu

Rakib Al-Fahad
Department of Electrical and Computer Engineering, The University of Memphis, 3815 Central Avenue, Memphis, TN 38152, Email: ralfahad@memphis.edu

Tao Ma, Ph.D., P.E.
Post-Doctoral Fellow, Department of Civil Engineering, Intermodal Freight Transportation Institute, The University of Memphis, 3815 Central Avenue, Memphis, TN 38152, Phone: (901) 462-7409, Email: tma@memphis.edu

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Executive Summary

Many of the products such as pharmaceuticals, biohazard material, and human organs are frequently shipped across regions, countries, continents, and hemispheres with different environment. During the shipment, these products should be preserved in a specific condition to prevent severe damage. Considerable amount of perishable products spoil before they reach consumers. To avoid spoilage and to maximize revenue of shipping high value, temperature controlled, perishable products, precise integration of the product, process, package, and distribution is critical.

In this study, besides conventional inventory and transportation network cost, we incorporate packaging cost in an optimization model with a single objective function that consists of different components: (i) packaging, (ii) storage, (iii) quality degradation, (iv) network congestion, (v) waste disposal, and (vi) potential supply chain of the perishable products; subject to capacity, shelf-life, supply chain, and other pragmatic product quality constraints. The proposed objective function is non-linear non-convex integer function. We adopted Nomad software to solve the optimization problem. Our main goal is to build a model that can optimize packaging cost of high value, temperature controlled, perishable products supply chain, and maintaining product quality. Due to the importance and critical nature of vaccine supply chain, in a numerical case study, the

proposed model has been simulated a simplified vaccine supply chain in order to minimize the logistic cost.

The result of the numerical study has shown that the cost related to the packaging of perishable products is significantly important. By considering the amount of packaging as a variable in our model, it has been shown that the cost of logistic can be reduced considerably. The different scenarios illustrate the capability of the model in considering various situations that are likely to occur in real world cases.

1 Introduction

Diversity of production, transportation, consumers' needs and services demands efficiency in supply chain management (SCM) are critical to the success of business operations. While products are frequently shipped across regions, countries, continents, and hemispheres with different environment, many of the products such as pharmaceuticals, biohazard material, and human organs, are temperature and time sensitive. To ensure that the supply satisfies consumer demand, supply chains of those items, consisting of complex networks of economic activities, should be optimized *(1)*.

Time is a significantly important factor in SCM of perishable items. Delays in delivering the products may impact the quality and quantity of the products. For example, radioisotope may have production time and must be used within a week in a hospital or medical facility

Proper packaging protects perishable products from environmental influence. During transportation, perishable items may be exposed to harsh environmental condition (i.e. temperature fluctuation, humidity). Insulation and refrigeration are the keys to preserve perishable items during their shipment *(2)*. Recently, there has been tremendous development in new perishable packaging technologies such as microwave packaging, aseptic processing, modified or controlled atmosphere packaging, and sous-vide (vacuum cooking) technology worldwide *(3)*. Most perishable packaging devices can be classified into two categories: (i) Active Cold Storage Devices (ACD) and (ii) Passive Cold Storage Devices (PCD) *(4)*. ACD use electric power and actively cool the inner product. PCD are not dependent on electricity and can maintain specific temperature for certain period of time using a passive medium of cooling and insulator *(4)*. ACD need continuous power supply during transportation and are not convenient due to limited resource and better product generalization. The major advantages of PCD are that (i) they do not need power supply, (ii) coolant can be changed manually for any unwanted delay or product quality degradation, (iii) they are convenient to handle and easy to implement tracking or monitoring device inside or outside the package, (iv) compatible with any transportation mode, and (v) most importantly the packaging can be optimized based on product type.

It was reported that 10% of all perishable product spoil before they reach consumers *(5)*. Therefore, precise integration of the product, process, package, and distribution is critical to avoid spoilage and private carriers are prudently considering optimal packaging with emphasis on effective distribution, network optimization, shipment consolidation, cross docking, supplier management, and supplier integration *(6)*.State-of-the-art practice for profit maximization in SCM is cost optimization in complex transport network, storage, and inventory system *(1, 9–12)*. In this study, besides conventional inventory and transportation network cost, we incorporate packaging cost in an optimization model with a single objective function that consists of different components: (i) packaging, (ii) storage, (iii) quality degradation, (iv) network congestion, (v) waste disposal, and (vi) potential supply chain of the perishable products; subject to capacity, shelf-life, supply chain, and other pragmatic product quality constraints. The proposed objective function is non-linear non-convex integer function. We adopted Nomad software*(11)* to solve the optimization problem. Our main goal is to build a model that can optimize packaging cost of high value, time-sensitive, perishable product supply chain, and maintaining product quality. Due to the importance and critical nature of vaccine supply chain, in a numerical case study, the proposed model has been simulated a simplified vaccine supply chain to minimize the logistic cost.

2 Literature Review

Nowadays, the supply chain is complex with broad spectrum. Specific modeling approach cannot capture all the aspects of supply chain processes. Supply chain has to deals with competitive strategic analysis include, demand planning, location-allocation decisions, strategic alliances, distribution channel planning, new product development, information technology (IT) selection, outsourcing, supplier selection, pricing, and network restructuring. Though most of the supply chain problems are static in nature, SCM needs to cope up with vehicle routing/scheduling, workforce scheduling, record keeping, and packaging. Some supply chain problems may involve hierarchical and multi-level planning that overlap different decision levels. To fill the gap between complexity and reality, modeling of supply chain require dealing with real-world dimension. There is no standard systematic way to solve ‘firm-specific’ supply chain problem (7). Stevens, Chopra and Meindl (12, 13) proposed guideline to model supply chain based on three levels of decision hierarchy consist of (1) operational routines, (2) tactical plans, and (3) competitive strategy. Another popular guideline is proposed by Copper et al. (14) consist of three structures of a supply chain network. These structures are: (1) type of supply chain partnership, (2) the structural dimensions of a supply chain network and (3) the characteristics of process links among supply chain partners.

2.1 Components of supply chain modeling

It is necessary to identify the key component to model supply chain. Those components may differ from one company to another (7), Some examples of those components are:

2.1.1 Supply chain drivers

The first step of supply chain modeling is goal setting. The major driving forces of the supply chain include customer service initiatives, monetary value, information/knowledge transactions, and risk elements.

2.1.2 Supply chain constraints

Constraints represent restrictions or limitations placed on a range of decision alternatives that a company can choose. Examples of constraints are capacity, service compliance, and the extent of demand. Definition of capacity includes the available space for inventory stocking and manufacturing capability. Supply chain member's production, supply, and technical capability determine its desired outcome regarding the level of inventory, workforce, production, outsourcing, IT adoption and capital investment. Service compliance is one of the most important constraints for example delivery time windows, maximum holding time for back orders, production due dates, and driving hours for truck drivers. On the other hand, the vertical integration of a supply chain balance the capacity of supply at the preceding stage against the extent of demand of the downstream supply chain members at the succeeding stage *(7)*.

2.1.3 Supply chain decision variables

Decision variables are functionally related to supply chain performances i.e. the objectives functions of a supply chain are generally expressed as a function of one or more decision variables. Examples of decision variable are as *(7)*:

- The location of production plants, warehouses, distribution centers, consolidation points, and sources of supply,

- Allocation of warehouses, distribution centers, consolidation points and production plants that should serve customers or suppliers accordingly,
- Timing of expansion or elimination of manufacturing or distribution facilities,
- Network structuring,
- Number of facilities and equipment,
- Number of stages (echelons),
- Service sequence,
- Optimal purchasing volume, production, and shipping volume at each node,
- Inventory level,
- Size of workforce.
- The extent of outsourcing.

The models for supply chain of perishable products can be classified as (i) deterministic and (ii) stochastic *(7, 15)*. For deterministic model approaches, the researchers have widely used mathematical techniques such as linear programming (LP), mixed integer programming (MIP), dynamic programming (DP), goal programming (GP). On the other hand, popular stochastic modeling approaches include simulation (SIM), stochastic dynamic programming (SDP), risk programming (RP) *(7)*. For example, Ferrer et al. *(16)* model the optimal scheduling of the harvest of wine grapes using a LP model with the objective of minimizing operational and grape quality costs. Widodo et al. *(17)* used DP modeling approach to integrate harvest, production, and storage of perishable items with growth and loss functions for maximizing the demand satisfied. Caixeta-Filho *(18)* deals with LP approach that relates biological, chemical, and logistics constraints to the quality of fruit product to harvest, with objective of maximizing revenue. For maximizing revenue, Kazaz et. al. *(19)* consider two-stage SP model to determine the olive trees to contract for an oil producer in the season with uncertain harvest and demand. TABLE 1 shows summary of some modeling approaches used for planning perishable product SCM.

Traditional SCM deals with a single objective function to minimize cost or maximize profit. *(9, 20–22)*. There are a large number of published studies that describe the quality evaluation based pricing model for perishable product supply chains. For example, Xiaojun et. al. *(23)* proposed a model to reduce food waste and maximize seller's profit. Their pricing approach was based on dynamically identified shelf-life using tracking and monitoring technologies. As product price cannot change frequently, they claimed that their proposed approach has advantage over conventional dynamic product pricing. Rong et. al.*(24)* presented a mixed-integer linear programming model for food product (bell peppers) SCM where product quality is related to temperature control throughout the supply chain. They formulated quality-based multi-period production and distribution planning problem by minimizing the cost function consisting of production costs, cooling costs for transportation equipment, transportation costs, cooling costs for storage facilities, storage costs, and waste disposal costs. Cost optimization was achieved with specific constraints for fresh food supply chain. Nagurney et. al. *(1)* emphasized on unified supply chain network analytics framework to handle optimization and competitive behavior relevant to perishable product market. They modeled generalized networks of supply chain problems for a wide variety of product and guidelines to determine the arc multipliers that capture perishability.

TABLE 1 Modeling approaches used for planning perishable product SCM

Author	Model type	Other aspects	Main Objective
Ferrer et al.(16)	LP, MIP	Relaxation heuristic	Optimally scheduling of wine grape harvesting
Widodo et al. (17)	DP	Growth and loss functions	Flowering–harvesting model
Caixeta-Filho(18)	LP		Orange harvesting scheduling management
Kazaz (19)	SP	Nonlinear optimization	Optimization of olive oil production
Allen and Schuster *(25)*	LP, MIP	Nonlinear optimization	Optimize crop harvest model
Rantala *(26)*	LP		Seedling SCM of multi-unit finish nursery company
Itoh et al. *(27)*	LP	Fuzzy programming	Optimize crop harvest model
Berge ten et al. *(28)*	SP	Multi-objective programming	Optimization in dairy farming, flower bulb and integrated arable farming.
Darby-Dowman et al.*(29)*	LP		Determining robust planting plans in horticulture
Romero *(30)*	LP	Risk programming	Agriculture SCM with multiple criteria decision-making risk analysis
Leutscher et al. *(31)*	SDP	Simulation and regression	Agricultural SCM optimization
Stokes et al.*(32)*	SP, MIP		Optimal production and marketing decisions for a nursery producing ornamental plant
Aleotti et al. *(33)*	LP		Optimize revenue by changing the capacity of food preservation facilities and considering the uncertainties in crop markets
Miller et al. *(34)*	LP	Fuzzy programming	Planning for production and harvesting of packing plant with an LP and fuzzy programs
Hamer *(35)*	LP	Decision support system	Planting and harvesting plan for fresh crops
Purcell et al. *(36)*	LP	Risk programming	Decision model for landscape land production.
Van Berlo *(37)*	LP	Goal programming	Determine sowing, harvesting and production plans.
Annevelink *(38)*	LP	Genetic algorithm	Determine plan for the location of pot plants inside a greenhouse.
Saedt et al.*(39)*	LP		Develop a plan for a pot-plant greenhouse with future plans and transition plans.

Packaging protects perishable product from environmental influences such as heat, light, dirt and dust particles, pressure, enzymes, spurious odors, microorganisms, insect’s gaseous emissions, the presence or absence of moisture. The major function of packaging is protection, preservation from external contamination, extension of shelf life, retardation of deterioration, and maintenance of quality and safety of packaged product. Precise integration of the product, process, package, and distribution is critical to avoid recontamination. The ideal packaging material should be resistant to hazards and should not allow molecular transfer from or to packaging materials*(5)*. Other important purposes of packaging are containment, convenience, marketing, and communication. Containment ensures a product from intentional dispersion or spill. Communication ensures link between consumer and suppliers. It contains impotent information such as weight, source, ingredients, lifetime, cautions for use required by law, nutritional value. Companies use packaging as a media for product promotion, marketing and branding*(40)*.

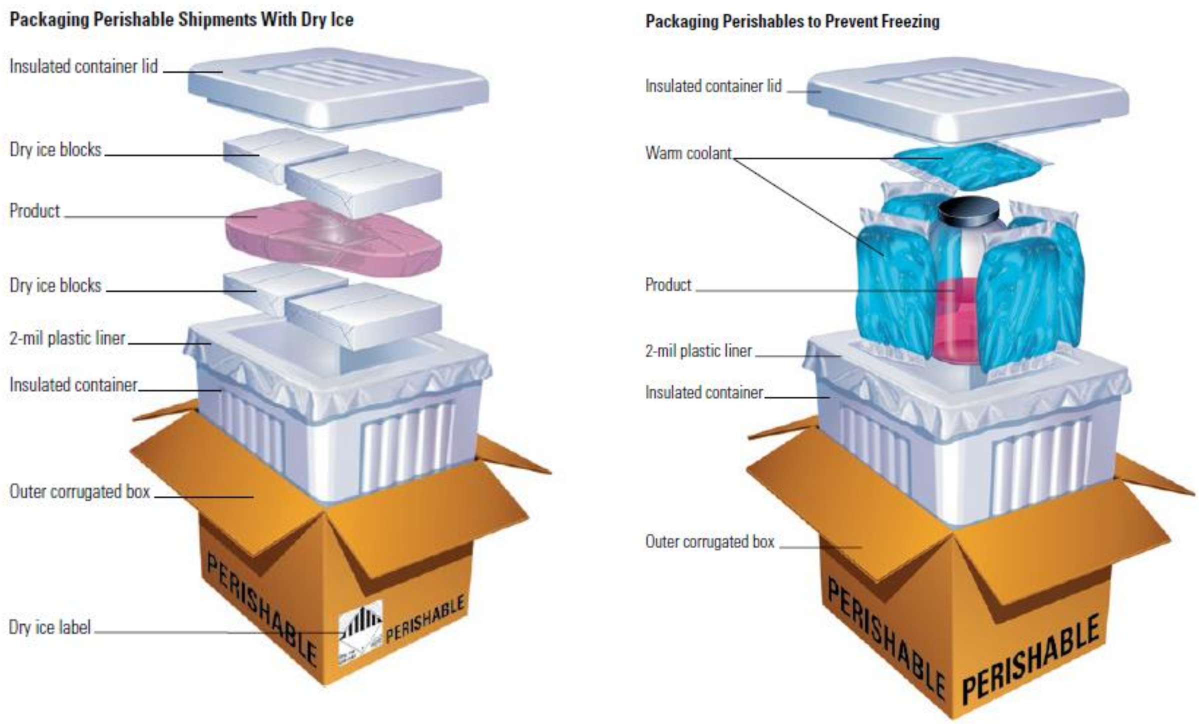


FIGURE 1 FedEx perishable product packaging process with dry ice and coolant (68)

Recently, there has been tremendous growth in new perishable packaging technologies such as microwave packaging, aseptic processing, modified or controlled atmosphere packaging and sous-vide (vacuum cooking) technology worldwide *(3)*. Major perishable packaging device can be distinguishing in two categories (i) active cold storage devices (ACD) and (ii) passive cold storage devices (PCD) *(4)*. ACD use electric power and actively cool the inner product. Some ACD are designed have backup system that can provide a specific temperature range up to 24 hours during power shortfalls or outages. PCD are not dependent on electricity and can maintain specific temperatures for certain periods of time using a passive medium of cooling and insulator. The most common used insulation materials are reflective materials, expanded polystyrene foam, and rigid polystyrene foam. Widely used refrigerants are gel coolant and dry ice *(4)*. ACD need continuous power supply during transportation. However, for limited resource and better product generalization, this technology is not convenient. The main advantages of temperature controlled express shipping service is that (i). It does not need power supply; (ii). Coolant can be changed manually for any unwanted delay or product quality degradation (iii) Convenient to handle and easy to implement tracking or monitoring device inside or outside the package. (iv) Compatible with any transportation e.g. truck, air cargo; most importantly (v) the packet can be optimized for product type hence cost effective.

Modern packaging technology deals with traceability, tamper indication, and portion control *(41)*. New tracking systems enable tracking of packages through the supply chain from production to consumers. Packages are imprinted with a bar code or universal product code to trace the product in the supply chain. Recently, intelligent or smart packaging is designed to monitor and communicate information about product quality (*(42, 43)*. For example, radio frequency identification, time-temperature indicators (TTIs), ripeness indicators, biosensors, and. These smart devices can be attached to package materials or the inside or outside of packages. The U.S. Food and Drug Administration (FDA) distinguishes TTIs in their Fish and Fisheries Products Hazards and Control Guidance (3rd edition), so their importance increased in the seafood industry. Home Depot, Wal-Mart, and famous retail outlets use radio frequency identification. This technology day by day become very prominent for tracking and tracing for perishable commodities. During transportation, perishable item may expose to harsh environmental condition e.g. temperature fluctuation, humidity. Insulation and refrigeration are the key to preserve perishable item during shipment. Due to vast improvement in packaging technology, the next generation packaging market revenue is expected to reach US$ 58 Bn by 2025 ("Next-Generation Packaging Market: Global Industry Analysis and Opportunity Assessment 2015-2025"- FMI research report). Recently there has been tremendous growth in new perishable packaging technologies such as microwave packaging, aseptic processing, modified or controlled atmosphere packaging and sous-vide technology worldwide*(3)*. There are thousands of patent at this area. Shipping giant company, like FadEx do not provide temperature controlled express shipping service. Instead proper use of insulation and refrigerant it is possible to maintain product within specific temperature. To monitor product quality, they use SenseAware technology*(44)*. The most common used insulation materials are reflective materials, expanded polystyrene foam, and rigid polystyrene foam. Widely used refrigerants are gel coolant and dry ice. Refrigerants keeps the product cold and frozen (keep consistent temperature) within specific life. Technology like refrigerated cooling packaging need continuous power supply. However, for limited resource and better product generalization this technology is not convenient.

It is observed that Total 10% of all perishable product spoil before they reach consumers *(5)*. Therefore, precise integration of the product, process, package, and distribution is critical to avoid spoilage. Profit maximization of complex multi-billion marked requires effective distribution, network optimization, shipment consolidation, cross docking, supplier management and supplier integration *(6)*. State of art practice for profit maximization in SCM is cost optimization in complex transport network, storage and inventory system(1, 9–12).

Recent improvement of computational efficiency enables us to use genetic algorithms (GA), fuzzy genetic algorithms (FGA) as well as an improved simulated annealing (SA) procedure of multi-objective optimization of SCM. For example, Nakandala et. al. *(22)* compared performance of those algorithm. They modeled fresh food supply chain in making cost optimized decisions regarding transportation, with the objective of minimizing the total cost and maintaining the product quality. On the other hand, modern complex SCM deals with outsourcing of production and distribution, product differentiation as well as quality and price competition, game theory is effectively and widely used *(1, 8)*. The summary of literature review suggests that the supply chain of time sensitive high-value commodities is emerging, and proven methodologies are yet to be established.

3 Methodology

This section provides a description of methodology for modeling and simulation of optimal packaging of high value, time sensitive, perishable products.

3.1 Packaging

Since perishable products on the way from their origins to destinations may be subject to harsh environmental conditions (such as excessive temperature), the careful packaging needs to be done to ensure the safe delivery of the products. The cost of the packaging needed for a certain perishable product mainly depends on the range of temperature control, the size of the package, the environmental condition, and the time length of the shipment. Based on the type of perishable product, the range of temperature control may change. For instance, in case of blood-related products the temperature control is between +2 °C to +8 °C to prevent freezing (freezing will damage the product). Size of the package is usually predefined, and it depends on the size of the product and the amount of protective material needed to keep the product safe. The size of the boxes, the shape of the products, the algorithm that used to pack the product inside of boxes, and the method for loading the container can considerably reduce the costs. Numerous studies can be found in the litrature in this area *(46, 46–48)*; however, it is not the concern of this study. Time length of the shipment directly affects the cost of packaging. Using an efficient system of cold storage, which minimizes the processing time, and optimizes the distribution of the shipments on the transportation network, would significantly reduce the time length of the shipment and consequently the cost of packaging.

There are different types of passive cold storage systems and the benefits of using them is explained in the introduction. Here we consider two of these systems which have been utilized by FedEx in packaging of perishable shipments. Some of the benefits of these systems include (but not limited to) (i) eliminating the need for refrigerated vehicles, (ii) easier and safer to switch modes of transportation, and (iii) improved storage capacity for a short time since there is no need for a refrigerated warehouse. Dry ice is usually considered for freezing condition, and coolant gel is considered for keeping the products cold (between +2 °C to +8 °C).

The amount of coolant gel or dry ice needed to keep the product at a certain temperature control determines a great portion of the packaging cost. These amounts can be estimated based on the following formulation under ideal (1)environmental conditions (73 ^{o}F and 50% relative humidity) *(49)***.**

$$Coolant = \frac{V_m * Tn}{Kc * CT} \tag{1}$$

Where V_m is the volume of the product; Tn is the time that the product needs to be in a temperature control; Kc is the constant for different methods of cooling system (for coolant gel it is 4147 and for dry ice it is 5184); to reduce the heat transfer through packaging container walls, commonly, expanded polystyrene foam has been used. The thickness of the foam (CT) depends on the environmental condition and usually it is between 0.5 to 2 inches. In order to protect the products from humidity and disturbance, sealed plastic bag, absorbent pads, proper outer box and other protective parts may be used, hence, the cost of them needs to be considered in the model.

Amounts of dry ice needed for different volume and time are illustrated in the FIGURE 2. For instance, 1 pound of dry ice would be enough to keep a 1000 (in3) product at the freezing condition for 10 hours while 2-inch foam is used.

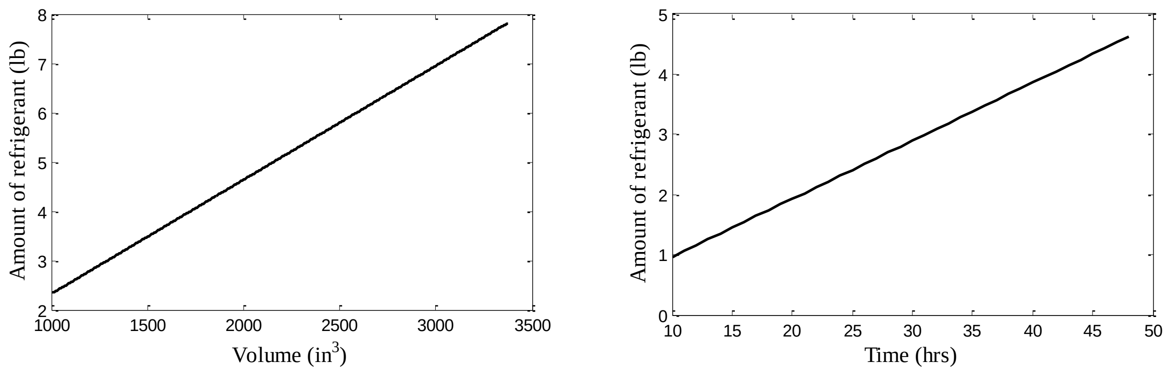


FIGURE 2 Illustration of amount of dry ice needed versus different volume for 24 hours (Left) and Illustration of amount of dry ice needed versus time for 1000 (in3) product (right).

3.2 Modeling quality degradation:

Due to various storage conditions, quality factors, product (2)features, predicting the quality of a product remains challenging. Most models for predicting the product quality are based on the assumption that there is normally one leading quality characteristic for a given product *(23)*. For instance, for the perishable food, the freshness of the products could be considered as the leading quality factor *(23)*, while in perishable pharmaceutical products the effectiveness (potency) of the product may be considered as the main quality attribute of interest. Most perishable products are at the highest level of their quality right after the production and over time the quality would decrease. For estimating the quality degradation, many models have been proposed for different products. The summary of these studies could be found in the deteriorating inventory literature *(50–53)*. In the present study, we have used the first-order reactions with exponential time decay which frequently has used in perishable food and pharmaceutical products *(23, 24, 54)*. The kinetic formulation can be expressed as:

$$\frac{dq}{dt} = -kq^n \tag{2}$$

Where q is the measured value of the chosen leading quality factor, n is the order of the reaction, determining whether the reaction rate is dependent on the amount of quality left *(23)*. Most often, power factor, n, will have a value of either 0 or 1 for linear to exponential degradation, respectively. k is the rate of degradation depending on environmental conditions like temperature and can be estimated by “Arrhenius Equation” as follows:

$$k = k_0 e^{-[E_a/RT]} \tag{3}$$

Where k_0 is the rate constant, E_a is the energy of activation for the reaction that controls quality loss, R is the gas constant, and T is the absolute temperature. Depending on n, Equation 3 can represent models for quality changes that follow a linear to exponential decay *(55)*. This means that we can estimate the quality level of a product at a certain location in the food supply chain based on an initial quality (q_0). For a time period with length τ, this leads to the Equation 4 and 5 for zero-order and first-order reactions, respectively.

$$q = q_0 - \tau\, k_0 e^{-[E_a/RT]} \tag{4}$$

$$q = q_0 \cdot e^{-\tau(k_0 e^{-[E_a/RT]})} \tag{5}$$

In practice, k is determined at a number of temperatures and the data set (k, T) are then analyzed by least-squares fitting procedure to form a linearized Arrhenius Equation. Taking the natural logarithm of both sides of Equation 3 yields:

$$\ln(k) = \ln(k_0) - \frac{E_a}{R} \cdot \frac{1}{T} \tag{6}$$

Thus, E_a/R and $\ln(k_0)$ can be obtained by calculating the slope and intercept of the fitted line.

3.3 Modeling

Various management decisions need to be made for a supply chain. With today's computing power, no model can consider all aspects of a real supply chain. For the sake of simplicity (without loos of generality) each model tries to approximate the reality and focuses on critical constraints. Time and environmental conditions are the main issues for perishable products since the quality of the products may degrade drastically by ignoring these two factors. For a large number perishable products, the major cost of controlling environmental conditions can be associated with the temperature control, and in many models, temperature is the main factor in quality degradation model *(24)*. Thus, in this study, product temperature and time are considered to be the main factors in estimating the quality degradation.

Each Product has a specific production process. In order to have a general model, production process is not considered in our model. However, this element can readily be considered for a specific product. The general representation of the supply chain model considered for this study is depicted in FIGURE 3 which primarily models the distribution and delivery services. Here, we consider a third-party logistics company that provides the logistic services between individual, enterprise suppliers, and consumers. At the logistic service provider (LSP) centers at the origin, the goods are collected from the suppliers, and they will be evaluated, labeled, packed, stored and prepared to be shipped to the consumers of the goods. Since the focus of this study is on high value, temperature controlled, perishable products, long-term storage should be avoided. On the way from the product origins to destinations, we might have several distribution centers (hubs) which form a transportation network. Each LSP at the origin may directly be connected to another LSP at the destination. In addition, each hub center may connect to another hub center that defines different paths between an LSP and a consumer.

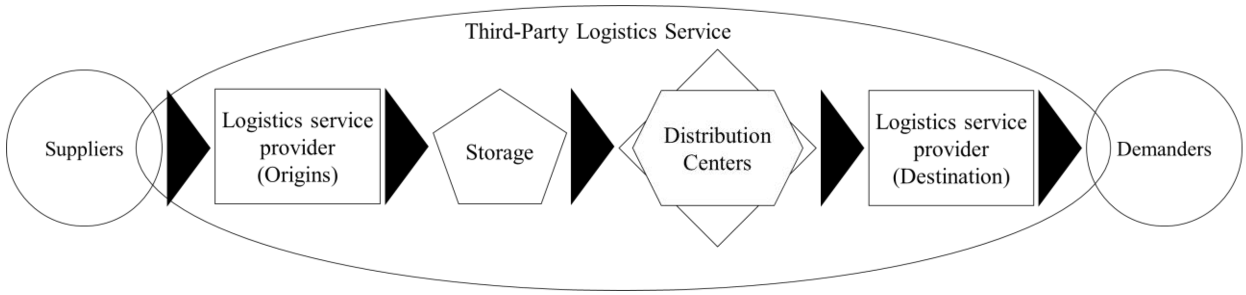


FIGURE 3 The supply chain structure

3.4 Model formulation:

3.4.1 Notation

The following notation is utilized to describe the model formulation.

3.4.2 Indices

t	Time step Index
a	Link number Index
d	O-D pair number Index
n	Path number Index
i	The number of LSP at the origin
j	The number of hub at the network
k	The number of LSP at the destination
a_i	An index to show the number of links that pass ith LSP at the origin
a_j	An index to show the number of links that pass jth hub at the network
a_k	An index to show the number of links that pass kth LSP at the destination
m	An index to show the type of package
c	An index to show the type of cooling method

3.4.3 Variables

$f_n^{d\,t}$	Flow at the nth path of dth O-D pair at tth time step.
t_a^0	Free flow time of the ath link in the network.
$P_{c\,m}^{d\,n\,t}$	Unit cost of type-m package with cooling method c for nth path of dth O-D pair and
v	The amount of wasted product.

3.4.4 Sets

A	Set of links
T	Set of time steps
D	Set of O-D pairs
N	Set of paths
G	Set of cooling methods
I	Set of LSPs at the origin
J	Set of hubs at the network
K	Set of LSPs at the destination

3.4.5 Constants

$\delta_{a\,n}^{d}$	Binary variable that shows if the link a is a part of path n connecting dth O-D pair
α_a	The constant that will be set based on the characteristics of the link a
C_a^t	The capacity of the link a at tth time step
β_a	The constant that will be set based on the characteristics of the link a
$N_{c\,m}^{n}$	Number of type-m packages with cooling method c
V_m	The volume of type-m packages
D_k^{limit}	Capacity of the kth LSP at the destination
H_j^{limit}	Capacity of the jth hub center
$O_{i\,t}^{limit}$	Capacity of the ith LSP at the origin at time step t
k_0^c	The rate constant for the quality degradation
q_{limit}	Allowable quality limit
E_a	The energy of activation for the reaction
R	The gas constant
$Temp^c$	The absolute temperature for the cth cooling type
t_{limit}^{d}	The maximum allowable time travel for dth O-D pair
I^t	The initial time at tth time step
$Supply^d$	The quantity of the supply for dth O-D pair
CT	The thickness of the foam

3.4.6 Unit costs

S_a^T	Unit cost of travel for the link a
$S_{i\,t}^{O}$	Unit cost of processing packages at ith LSP at the origin at time step t
S_j^H	Unit cost of processing packages at jth hub center
S_k^D	Unit cost of processing packages at kth LSP at the destination
W^d	Unit cost of waste disposal
$S_{m\,c}^{P}$	The fixed price for type-m package with cooling method c
S_C	Unit price of coolant material for cooling method

3.5 Objective function:

The objective function is presented in Equation 7. The goal is to find the flow in each path that minimizes the costs of logistic of high value, temperature controlled, perishable products between two LSPs or between one LSP and consumers. The costs consist of six parts: (i) transportation cost, (ii) processing and inventory cost at the LSP centers at the origin, (iii) processing cost at the hub centers, (iv) processing cost at the LSP centers at destination, (v) packaging cost, and (vi) waste cost.

Based on the common transportation models, time of the travel depends on the usage of each link *(56)*. Thus, the travel cost of each unit at a link in supply chain network is not fixed but rather depends partly on the usage of the link. In the proposed model, the unit cost of transportation for each link at a time interval depends on the congestion, mode of transportation, and characteristics of the link (such as free flow time and capacity of the link). The total cost of travels between different centers is considered as transportation cost.

$$min \sum_{t} \sum_{a} \left[\left(\sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a\,n}^{d} \right) * \left(t_{a}^{0} \left(1 + \alpha_{a} \left(\frac{1}{C_{a}^{t}} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a\,n}^{d} \right)^{\beta_{a}} \right) \right) * S_{a}^{T} \right] + \sum_{i} \sum_{t} \sum_{a_i} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_i\,n}^{d} * S_{i\,t}^{O} + \sum_{k} \sum_{t} \sum_{a_k} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_k\,n}^{d} * S_{k}^{D} + \sum_{j} \sum_{t} \sum_{a_j} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_j\,n}^{d} * S_{j}^{H} + \sum_{t} \sum_{d} \sum_{n} \sum_{m} \sum_{c} P_{c\,m}^{d\,n\,t} * N_{c\,m}^{n} + \sum_{d} W^{d} * v \tag{7}$$

Subject to

$$\sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a\,n}^{d} \leq C_{a}^{t} \qquad \forall a \in A, \forall t \in \tag{8}$$

$$\sum_{a} \left(t_{a}^{0} \left(1 + \alpha_{a} \left(\frac{1}{C_{a}^{t}} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a\,n}^{d} \right)^{\beta_{a}} \right) * \delta_{a\,n}^{d} \right) + I^{t} \leq t_{limit}^{d} \qquad \forall t \in T, \forall d \in D, \forall n \in N \tag{9}$$

$$q_0 \cdot \exp \left(- \left[\sum_{a} \left(t_{a}^{0} \left(1 + \alpha_{a} \left(\frac{1}{C_{a}^{t}} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a\,n}^{d} \right)^{\beta_{a}} \right) * \delta_{a\,n}^{d} \right) + I^{t} \right] * \left(k_0 e^{-\left[\frac{E_a}{RT}\right]} \right) \right) \geq q_{limit} \qquad \forall t \in T, \forall d \in D, \forall n \in N, \forall c \in G \tag{10}$$

$$\sum_{a_i} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_i\,n}^{d} \leq O_{i}^{limit} \qquad \forall i \in I, \forall t \in T \tag{11}$$

$$\sum_{a_k} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_k\,n}^{d} \leq D_{k}^{limit} \qquad \forall k \in K, \forall t \in T \tag{12}$$

$$\sum_{a_j} \sum_{d} \sum_{n} f_{n}^{d\,t} * \delta_{a_j\,n}^{d} \leq H_{j}^{limit} \qquad \forall j \in J, \forall t \in T \tag{13}$$

$$\sum_{t} \sum_{n} f_{n}^{d\,t} = Supply^{d} - W^{d} \qquad \forall d \in D \tag{14}$$

$$f_n^{d\,t} \in \mathbb{Z}^+ \quad \forall d \in D, \forall t \in T, \forall n \in N \tag{15}$$

$$P_{c\,m}^{d\,n\,t} = \frac{V_m * \left[\left(\sum_a t_a^0 \left(1 + \alpha_a \left(\frac{1}{C_a^t} \sum_d \sum_n f_n^{d\,t} * \delta_{a\,n}^d\right)^{\beta_a}\right) * \delta_{a\,n}^d\right) + I^t\right]}{K_c * CT} * S_C + S_{m\,c}^P \tag{16}$$

At each logistic service centers at the origin, the products will be received, labeled and stored for an appropriate time for shipment to their destination. The cost of storage, labor cost and other expenses in these centers simplified in the second term of the objective function. Similarly, the third part of the cost function account for the cost of LSP centers at the destination.

Between each LSP center, there could be several hub centers. In each hub based on the mode of travel, some routine tasks need to be done for each package. The cost related to these activities can be expressed in the fourth part of the cost function. It is worth mentioning that the cost for each center could be different from the other centers, and these values need to be defined for each center.

The fifth term in the Equation 7 estimates the cost of the cooling package. Based on the Equation 1, the unit cost of packaging ($P_{c\,m}^{d\,n\,t}$) depends on the type of package, cooling method, and the time of the travel which can be estimated by Equation 16. At the first part of this equation, the amount of refrigerant material needed for the package is estimated (based on Equation 1) and multiplied by the unit cost of the material. A fixed cost is added to account for the cost of sealed plastic bag, absorbent pads, Expanded polystyrene foam, and outer corrugated box.

Depending on the value of the product, there should be a penalty for the wasted product (product that did not meet the quality limitations). In estimating the value of a product, not only the production cost and disposal cost should be considered, but also the negative social impacts of losing the product should be estimated. For instance, in the case of shipping human organs, the waste of the shipment may jeopardize the life of a patient, or in the case of food industry the loss of the product may lead to costumer's dissatisfaction. The last term in the objective function addresses the waste cost.

3.6 Constraints:

The constraints considered in our model can be divided into eight general categories as represented in Equations 8-15. The first set of constraints, Equation 8, ensures that the flow on each link is less than the capacity of the link at all of the time steps. The flow in a link can be calculated based on the flow on the paths that contain the link. The second set of constraints limits the time travel between each O-D pair. The time of the shipment for a perishable product should be less than the shelf-life of the product as indicated in Equation 9. The quality degradation of the product can be controlled by the set of inequalities at the Equation 10. These set of constraints are formulated based on the first-order degradation model described in Equation 6. If all of these two sets of constraints satisfied (time and quality constraints), there would be no waste in the shipment. The amount of products that fail to satisfy these constraints would be considered as waste costs in the cost function. The sets of constraints at the Equations 11 and 12 prevent the LSP center at the origin and destination from being overload. Similarly, Equation 13 assures that the flow that passes through each hub is less than the capacity of the hub. Flow conservation constraints at the Equation 14 check that the summation of the flow on all paths connecting each O-D pair to be equal to the quantity of the products that need to ship between that O-D pair. The last constraint, Equation 15, represents integer and non-negativity nature of variables to limit the search space to and to obtain physically meaningful solutions.

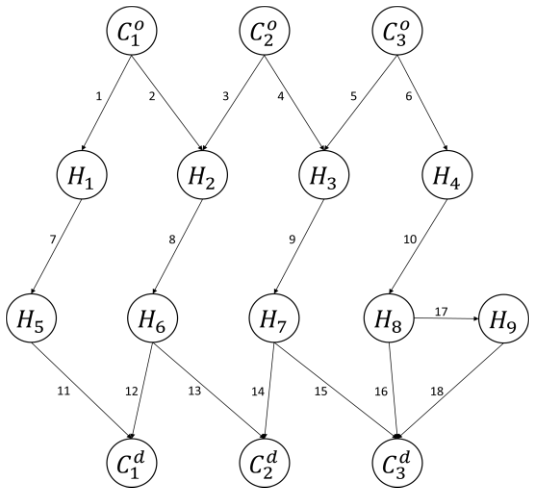
4 Numerical Experiment (Vaccine logistic)

Despite many efforts, immunization programs are struggling to meet the demands of routine immunization and supplemental campaigns, and the existing systems cannot keep pace with the changing landscape of immunization programs (15, 57). For instance, based on WHO (15, 57) 2.8 million vaccine doses lost in five countries due to cold chain failures in 2011. Thus, the proposed model has been simulated as a simplified vaccine logistic system to minimize the logistic cost while keeping the quality of the product in a certain range by considering the proper amount of packaging.

The leading quality factor for most vaccines is the potency of the vaccines. The simplest plausible model for vaccine potency degradation is first-order kinetics *(58)*. In this case study, we are assuming a hypothetical vaccine based on *(58)*. In order to control the quality of the product, we limit the potency to 80% of the initial potency which here we assumed it as 100% for all vaccine.

Many vaccines consist of proteins that may rapidly break down and become ineffective when exposed to temperatures above 10 °C and therefore must remain in environment with strictly controlled temperatures *(4)*. To ensure that the vaccines are kept in the proper condition, we used insulated boxes described in section 2. Enough coolant gel for keeping the temperature of the product between 2-8 ^{o}C for the entire time of storage and travel is considered for each package. Thus, in calculating the rate of degradation (k) the average temperature of 5 ^{o}C (278 Kelvin) is used.

The transportation network considered here is between the three LSP centers at the origin which transport the vaccines to the LSP centers at the destination through two or three hub centers. The configuration of the network is depicted in FIGURE 4.The LSP centers that receive the products from the suppliers are at the top tier which transports the product to the specified LSP centers at the last tier of the network. The second and third tiers of the network consist of hub centers that help to distribute the flow in the network. These different centers are connected with 18 links of transportation. These links could be associated with the various modes of transportation, but, for the sake of simplicity, all the links are assumed to be roads, and the products are shipped by trucks. Based on the transportation network, we have considered six O-D pairs and ten paths between them. The information of each path along with the set of links that forms each path are shown in FIGURE 4. The free flow, the capacity of each link, and the parameter related to characteristic of the link are presented in TABLE 2 *Transportation network information* Moreover, the time delay in each center is a random number between 1 to 2 hours and the delay in each path can find in the appendix.



Path and link connections

Path number	O-D pairs	Origin	Destin	Set of Links
1	1	C_1^o	C_1^d	1, 7, 11
2	1	C_1^o	C_1^d	2, 8, 12
3	2	C_1^o	C_2^d	2,8,13
4	3	C_2^o	C_2^d	3,8,13
5	3	C_2^o	C_2^d	4,9,14
6	4	C_2^o	C_3^d	4,9,15
7	5	C_3^o	C_2^d	5,9,14
8	6	C_3^o	C_3^d	5,9,15
9	6	C_3^o	C_3^d	6,10,16
10	6	C_3^o	C_3^d	6,10,17,18

FIGURE 4 The configuration of the 18-line network.

As explained before we are considering passive cooling system with coolant gel. Considering ideal environmental conditions (73 ^{o}F and 50% relative humidity) Equation 1 is used for calculating the amount of coolant assuming the thickness of the insulating foam is 0.5 an inch. We have considered three sizes of boxes to pack the appropriate amount of vaccine for the consumers as shown in TABLE 3 *Demand in each O-D pair.* The volume of the vaccine is expressed by number of boxes with different sizes. In addition, for the practical issues, we assumed that only 70% of the volume of the container of a truck (150x80x80 inch) could be filled. The supply and demand for each O-D pairs in term of number of boxes and number of trucks are tabulated in TABLE 3 *Demand in each O-D pair.* Based on the amount of demand we are considering two-time steps, and the whole time horizon is two days. By increasing the demand, the travel time and delay at the LSP and hub centers would increase, and consequently, the quality of the product would decrease. In this situation, the time step interval needs to be shorter which directly depends on the LSP equipment and machinery to avoid the drastic quality loss. Developing an LSP is not always possible, in result, in some cases having waste of product is inevitable. In this case study, the demand is selected based on the capacity of the LSP and supply chain network; therefore, by distributing appropriate flow in each path the wastage of the vaccine is prevented.

Although we tried to estimate realistic values of the unit costs for different part, many factors may change these values, and they should be set at the beginning for a specific situation. Here we assumed that the unit cost of travel for each truck for one hour (S_a^T) is equal to \$150 for all links; the unit cost of inventory and processing for all centers is a number between \$500 to \$1000 for each truck and the overall cost for each path is tabulated in the appendix. The unit cost of coolant gel is \$0.5 for each pound; the fixed cost for the small, medium, and large boxes are equal to \$0.4, \$0.5, and \$0.6, respectively; To avoid any waste in our products, we set a large number for the unit cost of waste. Thus all of the products have their minimum quality requirement and no vaccine would be wasted.

TABLE 2 Transportation network information

Link Number	Capacity (Trucks)	Free Flow Time (hr.)	α	β
1	4800	6.25	0.15	4
2	5000	6.25	0.13	4.1
3	5000	6.25	0.1	3.9
4	4000	6.25	0.12	3.8
5	4000	6.25	0.13	3.5
6	4000	6.25	0.125	3.2
7	5000	6.25	0.128	3.3
8	8000	6.25	0.127	3.4
9	6000	6.25	0.13	3.9
10	4500	6.25	0.132	4.2
11	4500	6.25	0.133	4.6
12	4500	6.25	0.134	4.2
13	4000	6.25	0.136	3.3
14	4000	6.25	0.139	3.8
15	2000	6.25	0.138	3.2
16	2500	6.25	0.14	3.6
17	4000	5	0.14	3.6
18	4000	1.25	0.15	3.2

TABLE 3 Demand in each O-D pair.

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	8460000	7040000	7660000	6300
2	4704000	2324000	3500000	2800
3	10528000	8340000	5620000	5600
4	8160000	5600000	4020000	4000
5	8496000	5040000	3420000	3600
6	5544000	6300000	8400000	6300

The proposed objective function is nonlinear, and the search space is nonconvex and is limited to integer values. In such cases the objective function is very expensive to evaluate as optimization process requires multiple feedback between decision variable selection and constraints in the feasible region search process during step size and direction finding evaluation. Often, it is difficult to accurately obtain the derivate of the objective function. Solving large problem instances requires heuristics to approximate and relax the feasible region search process for faster convergence to obtain an optimal value without any guarantee of global optimality. To solve the proposed optimization problem we have used an non-linear integer constrained off the shelf solved called NOMAD available in opti-toolbox as an add-on to MATLAB *(11)*.

5 Results

Given the scenario presented in the previous section, the optimization problem is solved, and the result is shown in TABLE 4 Number of trucks that pass on each path, the remaining quality of the vaccines and amount of coolant needed for each package.. In some cases, although all of the flow could pass through one path, because of the congestion in the links and centers, the optimum solution happens when the flow is distributed between different paths. The amount of coolant for various size of boxes in each path are shown in TABLE 4 Number of trucks that pass on each path, the remaining quality of the vaccines and amount of coolant needed for each package.. Because of the characteristic of the transportation network (the travel time in each path is about the same range), there are small changes in the amount of needed coolant in one type of package. Nevertheless, the difference from a time step to the other one is significant. For instance, there is 4.3 lb. different between the coolant needed for day 1 and day 2 for each large box. Multiplying this number by the number of large boxes, one can realize that there is an enormous saving of coolant comparing to the case that the amount of coolant is selected regardless of the step time and the flow in each path. This shows the importance of the optimum cold packaging in the logistic of high value, temperature controlled, perishable products.

TABLE 4 Number of trucks that pass on each path, the remaining quality of the vaccines and amount of coolant needed for each package.

Path number	***Flow in each path***		***Remaining Quality (%)***		***Day 1***			***Day 2***		
	Day 1	Day 2	Day 1	Day 2	Small box	Medium box	Large box	Small box	Medium box	Large box
1	1942	0	90.8	100.0	0.7	1.3	3.9	0.0	0.0	0.0
2	0	4358	100.0	80.3	0.0	0.0	0.0	1.5	2.9	8.9
3	2800	0	90.7	100.0	0.7	1.3	4.0	0.0	0.0	0.0
4	0	3642	100.0	80.4	0.0	0.0	0.0	1.5	2.9	8.9
5	0	1958	100.0	81.3	0.0	0.0	0.0	1.4	2.7	8.4
6	2000	2000	90.3	81.0	0.7	1.3	4.1	1.5	2.8	8.5
7	3000	600	90.4	81.6	0.7	1.3	4.1	1.4	2.7	8.3
8	0	0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
9	2498	2059	90.0	81.5	0.7	1.4	4.3	1.4	2.7	8.3
10	1502	241	89.5	80.9	0.8	1.4	4.5	1.5	2.8	8.6

Note: NA represents Not applicable

The optimum cost and the contribution of different parts of the logistic cost are shown in FIGURE 4. It is observed that considerable portion of logistic cost is the packaging cost. Although in different situations, the percentages are shown in the diagram may change, the packaging cost for high value, temperature controlled, perishable products seems to be a considerable cost. Considering this cost as a separate cost in our model helps to find the optimum flow that leads to the minimum total logistic cost of the supply chain.

As an instance of advantages of optimizing the logistic cost based on the proposed model, the cost of logistic is calculated when the flow is distributed to the shortest paths without considering congestion. Comparing the result shows that the cost is 13% larger than the cost based on the proposed model. In the case where the flow is distributed evenly between different paths the cost is 43% larger than the cost based on the proposed model. Flow in each link and the flow that passes through each center are tabulated and are added to the appendix.

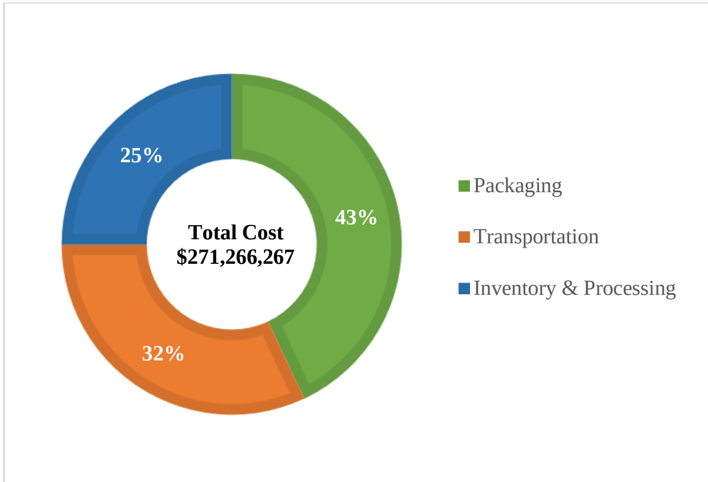


FIGURE 5 The total cost of logistic and the contribution of each part.

5.1 Elimination of packaging cost

To investigate the effect packaging cost on the flow pattern, we have solved the optimization problem without considering the cost of cold packaging. The cost associated with the optimum flows derived at this condition is 28% larger ($76,289,771 more) than the optimum cost considering the cold packaging cost in the model. This example clearly shows the importance of the cold packaging cost in determining the optimum flow on the transportation network. The numerical result of this experiment is in the appendix.

5.2 Reduction in capacity

The capacity of each link and centers may vary at different hours of a day. Moreover, because of adverse climatic conditions, the capacity of one or more links of the network will most likely be partially or completely disrupted for a specific time interval. The advantage of the proposed model is that it can account for such disruptions. To realize the effect of capacity change, we assumed the capacity of the of link 8, 16, and 17 on the first day would reduce by 5000, 1500, and 2000, respectively. These reductions happen just on the first day, and on the second day the capacity would be restored to original state. Comparing the cost for the new condition with the original cost, there is a 2% ($4,995,778) increase in total cost. That happens because a significant portion of the flow has been shifted to the second day and, in turn, the cost of inventory and packaging has been increased.

TABLE 6 The flow in each path

Path number	Day 1	Day 2
1	1900	0
2	0	4400
3	2800	0
4	0	3600
5	0	2000
6	2000	2000
7	3000	600
8	0	0
9	1000	2076
10	2000	1224

5.3 Reduction in demand

In order to investigate the effect of demand on the optimum solution series of experiments have been done. In these experiment the demand of all O-D pairs is gradually reduced to 50% and the optimization problem is solved for the reduced demands. To compare the cost, each part is divided by demand and is normalized with respect to 1. The result has been shown at the FIGURE 6. It can be seen from the graphs that the total cost is decreasing with the reduction of demand. This reduction is more significant for the packaging cost. By reducing demand, the time of travel would decrease and consequently the amount of coolant would decrease and the cost of packaging and transportation would decrease as well. The inventory cost is not sensitive to the demand since this cost is not affected by the time of the travel. The detailed numerical result is added to the appendix.

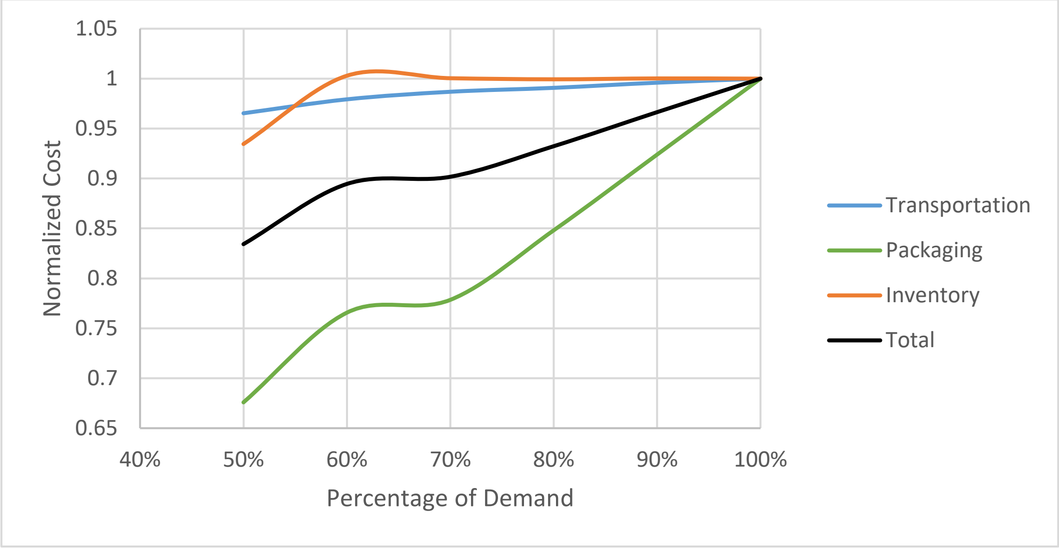


FIGURE 6 Variation of normalized cost for different parts.

6 Future Challenges

6.1 Environmental issue

Dry ice or carbon dioxide solid (UN 1845) is dangerous and hazardous material for air transport. Dry ice changes to carbon dioxide (CO2) gas and accumulate in enclosed spaces like aircraft cargo holds. It displaces oxygen, therefore, requires special handling and care (regulated by Federal Regulations Code: 49CFR). The design and construction of packaging used for dry ice shipments must prevent the buildup of pressure and cracks. Dry ice must never be placed in an airtight container. Overall, in different stages of perishable product packaging, we emit Carbon Dioxide direct to the environment.

Carbon dioxide is the major greenhouse gas, emitted by human activities. In 2014, about 80.9% of U.S. greenhouse gas was CO2*(59)*. Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle. Industrialization is changing the carbon cycle by adding more CO_2. While CO_2 emissions come from a variety of natural sources, human-related emissions are responsible for the increase that has occurred in the atmosphere since the industrial revolution. Total Emissions of CO2 in 2014 was 6,870 Million Metric Tons of CO2 equivalent. U.S.

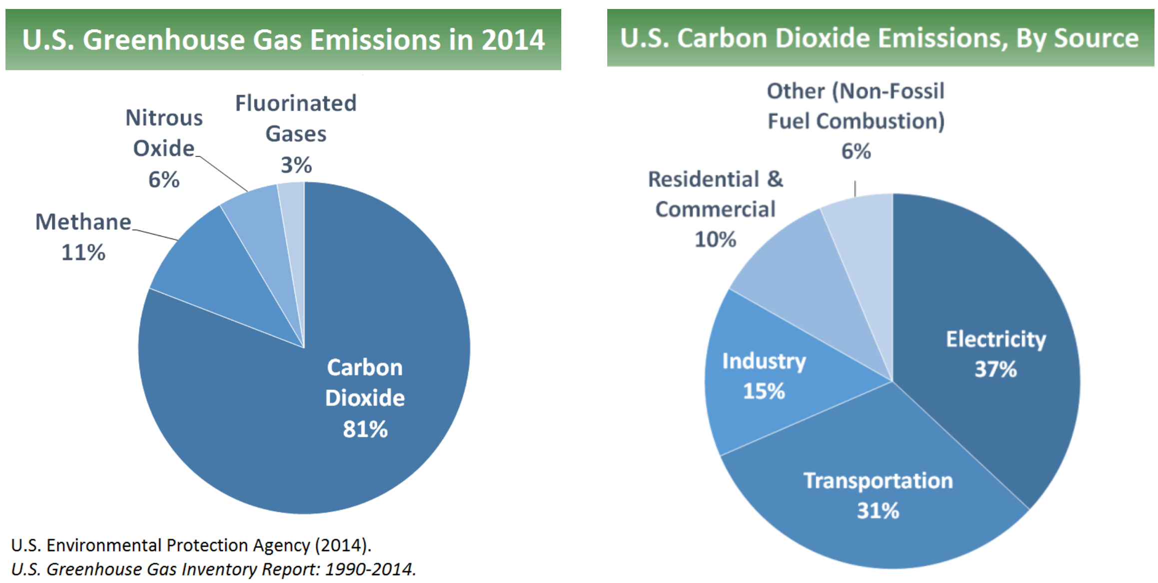


FIGURE 6 U.S. greenhouse gas emission in 2014 and their main sources (59, 60).

Excessive emission of CO2 has a great impact on the greenhouse effect and global warming. There are two major effects of global warming: Increase of temperature on the earth by about 3° to 5° C (5.4° to 9° Fahrenheit) and sea levels will rise by at least 25 meters (82 feet) by the end of this century.

Globally dry ice is used in Healthcare, Food Processing, Industrial Cleaning, Packaging and Transport sectors*(61)*. The Global Dry Ice Industry Report 2015 shows the alarming increasing demand for dry ice. Flourishing of this industry may bring a disaster in natural carbon circle. In our research, we found a significant gap between the use of production, use, refurbish and reuse and optimization of dry ice. There is no such market analysis and guideline for:

1. Market size of dry ice and coolant for packaging industry,
2. Safe and secure dry ice production process to reduce environment impact,

3. Proper instruction to use/reuse and refurbish dry ice,
4. Optimize the amount of coolant use to minimize climate effect,
5. The treatment plants for waste disposal.

6.2 Big data

Amazon uses big data to monitor, secure, and track 1.5 billion items in its inventory that are placed around 200 fulfillment centers around the different geographical location. Amazon relies on predictive analytics for its ‘anticipatory shipping’ to predict when and where a customer will purchase a product, and pre-ship it to a distribution center close to the final destination or customer*(62)*. On the other hand, Wal-Mart handles more than a million customer transactions each hour. Their RFID tracking system generates more than 2.5 petabytes of data which is 100 to 1000 times the data of conventional bar code systems *(63)*. UPS used telematics technology in their freight segment to redesign logistical networks *(64)*. Sipping giant company like FadEx do not provide temperature controlled express shipping service. To monitor product quality, they use SenseAware technology *(44)*. SenseAware measures environmental conditions on the unit level, such as: (1) Current location, (2) Relative humidity, (3) Temperature, (4) Light exposure, (5) Barometric pressure, (6) Shock detection, (7) Route alert, (8) Time based location alert. For audit, customer complaint or process improvement initiative, SenseAware preserves this enormous amount of data for a certain amount of time. TABLE 5 Some examples big data in SCM *(65).*

TABLE 5 Some examples big data in SCM *(65)*

SCM lever	Functional problem	Type of data
Marketing	Sentiment analysis of demand and new trends	Blogs and news, feeds, ratings and reputation from 3rd parties, weblogs, loyalty programs, call centers records, customer surveys
Procurement	Informing supplier negotiations	SRM Transaction data, Supplier current capacity & top customers, supplier financial performance information
Warehouse Operations	Warranty Analytics	Internet of things sensing, user demographics, historical asset usage data
Transportation	Real-time route optimization	Traffic density, weather conditions, transport systems constraints, intelligent transportation systems, GPS-enabled Big Data telematics

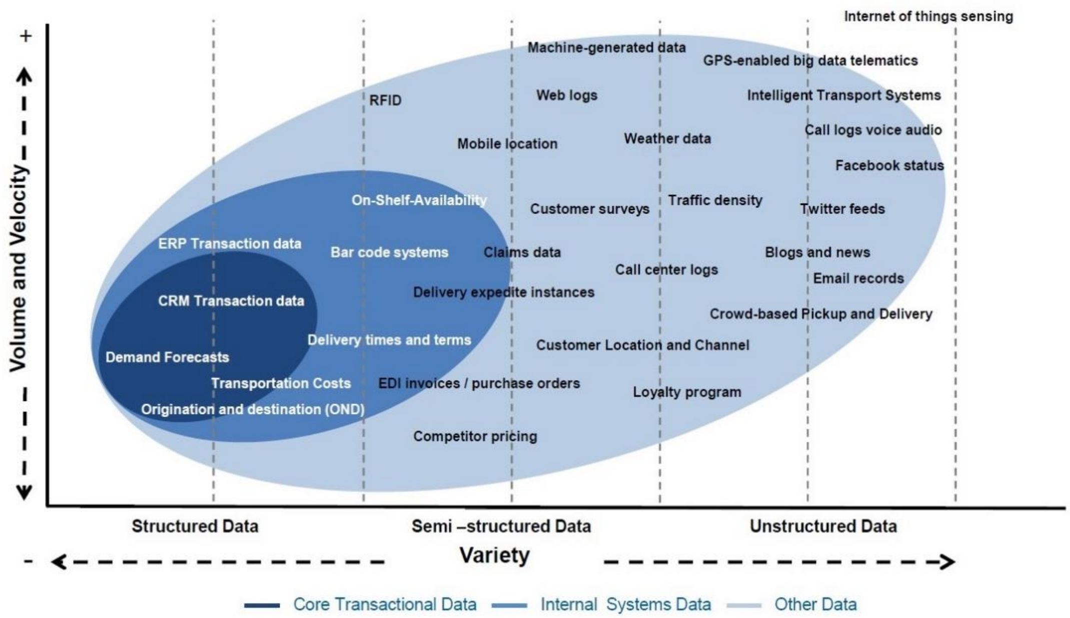


Figure 7 Volume and Velocity vs. Variety of SCM Data (67)

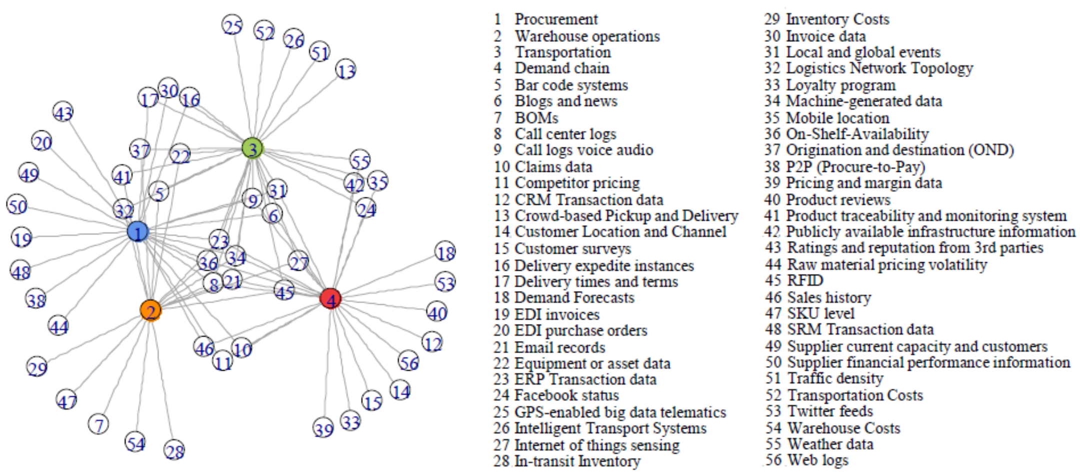


Figure 8 Example of a Big Data sources across SCM (Kamada-Kawai Network)(67)

Figure 7 Volume and Velocity vs. Variety of SCM Data (67) shows Volume and Velocity vs. Variety of different SCM Data *(65)* and a Kamada-Kawai network example consist of distance forces between the 52 data sources and each of the four SCM levers (Marketing, Procurement, Warehouse Management and Transportation) respectively. Eventually, SCM organizations are flooded with "huge and complex" big data. To notice such size and complexity, McAfee et al. *(64)* described that "business collect more data than they know what to do with". Big data analysis is practical problem for modern enterprises. Now a day's profit and success of a company depend on those big data analyses.

In this study, we attempt to investigate the optimal packaging of high value, temperature controlled, and perishable products by considering the effects of the supply chain, quality degradation, network congestion, and storage. This model can be useful for 'firm-specific' supply chain problem but a practical optimization approach should consider realistic constraints that come from these big data mining (for example mining on data, come from traffic density, weather conditions, transport systems constraints, intelligent transportation systems, GPS-enabled big data telematics) for better generalization. Most of the model implementation approach avoid incorporating SCM big data because those data are not publically available and trade secrets.

6.3 Collaboration between packaging and supply chain

Intelligent packaging contains components that enable the monitoring the condition of packaged product and the environment (inside and surrounding the product) during transport and storage*(66)*. This technology is an extension of the communication function of traditional packaging system. Intelligent packaging system provides customer reliable and correct information on the conditions of the product, packaging integrity, and the environment. It improves the overall performance of supply chains and wastage reduction *(66)*.

Conventional package manufacturing systems are based on a one-way flow of materials, from cradle-to-grave (C2G). As it is a one-way flow out of the factory, the manufacturer loses the value of reusing the material. The C2G design approach is based on 'taking, making and wasting' and a major contributor to environment pollution and greenhouse effect *(66)*. Hence, eco-efficiency strategies come forward to promote consumption reduction, prevention of waste and emissions, lifespan extension of products, and reduction of the effects, without suggesting a real alternative to the C2G material flows*(67, 68)*. Eco-efficiency strategies thus only focus on the reduction of environmental impacts made by human activity. Rather than seeking to eliminate waste afterward, Braungart et al.*(68)* proposed 'cradle-to-cradle (C2C)' framework which directly deals with maintaining resource quality and productivity through many cycles of use.

Packaging materials should be as cheap as possible. However, this industrial demand for cost optimization leads packaging design to multilayer composites or laminates that are difficult to reuse or recycle. The lack of foresight in the design of packaging and the extensive use of many different materials inevitably results in (1) reduced performance and attractiveness of recycled packaging, (2) complicated and expensive recycle processes, and (3) down-cycling of packaging materials *(68)*. Production cost of intelligent devices can be kept low by mass production. Therefore, those devices are often considered as relatively cheap and disposable.

Figure 9 Transportation of vaccines in a rural area of Nicaragua by horseback ***(69)***

Traditional packaging approach is firm-specific. Using our model it is possible to determine how much coolant is optimal, what should be the optimal size of package. Our proposed model has not only scope for optimizing the use of coolant but also room for optimization of package size. Our target is to effectively transport perishable product anywhere in the world, even in the rural area with harsh environment like in Figure 9. Implementation of intelligent, eco-friendly, cost effective packaging requires a multidisciplinary, collaborative and cross-sectoral approach. A sustainable packaging coalition needs to establish to gradually introduce the C2C design approach in the packaging industry.

7 Conclusions

This study attempts to investigate the optimal packaging of high value, temperature controlled, and perishable products by considering the effects of supply chain, quality degradation, network congestion, and storage. To the best of authors' knowledge, there is no study in the literature of perishable supply chain management that explicitly attempts to model the cost of packaging along with the transportation and inventory expenses for high value, temperature controlled, and perishable products. This study attempts to quantitatively model optimal packaging strategies by considering cold packaging technologies, their supply chain, reliability needs, and other pragmatic constraints

In the numerical case study, we applied the model to vaccine supply chain considering stylized small scale transportation network. By changing the demand at each O-D pair and by reducing the capacity of some links at one of the time steps, different scenarios have been defined and solved. The result has shown that the cost related to the packaging of perishable products is significantly important. By considering the amount of packaging as a variable in our model, we have shown that the cost of logistic can be reduced considerably. This reduction in cost, not only happens when the amount of refrigerant material is optimized which may save thousands ton of material, but also happens to the transportation cost and inventory cost. The different scenarios illustrate the capability of the model in considering various situations that are likely to occur in real world cases. In addition, the effect of these changes on the optimum cost has been discussed. While the proposed optimization approach provides a theoretical foundation to model optimal packaging of high value, temperature controlled, and perishable products, there are number of limitations to be addressed. The quality degradation function and amount of coolant needed can be calibrated with thermal properties of various type of material properties based on stress and climatic condition tests. In reality, long distance shipping encompasses various segments of roadway networks that are exposed to different climatic conditions and such measures need to be incorporated in the optimal packaging model. The scenario analysis only considers two types of uncertainties, namely, demand and disruption. In the future more uncertain scenarios (e.g., repackaging in the event of timely delivery) can be examined to assess the sensitives of the model and its results.

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9 Appendices

Appendix A

First Experiment

TABLE A-1. Time delay in each path (hr).

Path Num	Day1	Day2
1	3	3
2	5	5
3	3	3
4	5	5
5	3	3
6	3	3
7	3	3
8	3	3
9	3	3
10	5	5

TABLE A-2. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	4742	4358	8000	8000
2	2000	7600	8000	8000
3	7000	2900	8000	8000
4	1942	0	5000	5000
5	2800	8000	8000	8000
6	5000	4558	8000	8000
7	4000	2300	5000	5000
8	1942	0	5000	5000
9	2800	8000	8000	8000
10	5000	4558	5000	5000
11	4000	2300	5000	5000
12	1502	241	5000	5000

TABLE A-3. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	Day2	Day 1	Day2
1	1942	0	4800	4800
2	2800	4358	5000	5000
3	0	3642	5000	5000
4	2000	3958	4000	4000
5	3000	600	4000	4000
6	4000	2300	4000	4000
7	1942	0	5000	5000
8	2800	8000	8000	8000
9	5000	4558	6000	6000
10	4000	2300	4500	4500
11	1942	0	4500	4500
12	0	4358	4500	4500
13	2800	3642	4000	4000
14	3000	2558	4000	4000
15	2000	2000	2000	2000
16	2498	2059	2500	2500
17	1502	241	4000	4000
18	1502	241	4000	4000

TABLE A-4. Costs.

Inventory Cost	$70035700
Packaging Cost	$115368238.6
Transportation Cost	$85862329.2
Total Cost	$271266267.8

Elimination of packaging cost experiment

TABLE A-5. Flow in each path

Path number	Day 1	Day 2
1	3220	1304
2	1776	0
3	1565	1235
4	2435	2344
5	634	187
6	2000	2000
7	2365	1235
8	0	0
9	2497	2068
10	893	842

TABLE A-6. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	6561	2539	8000	8000
2	5069	4531	8000	8000
3	5755	4145	8000	8000
4	3220	1304	5000	5000
5	5776	3579	8000	8000
6	4999	3422	8000	8000
7	3390	2910	5000	5000
8	3220	1304	5000	5000
9	5776	3579	8000	8000
10	4999	3422	5000	5000
11	3390	2910	5000	5000
12	893	842	5000	5000

TABLE A-7. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	**Day2**	**Day 1**	**Day2**
1	3220	1304	4800	4800
2	3341	1235	5000	5000
3	2435	2344	5000	5000
4	2634	2187	4000	4000
5	2365	1235	4000	4000
6	3390	2910	4000	4000
7	3220	1304	5000	5000
8	5776	3579	8000	8000
9	4999	3422	6000	6000
10	3390	2910	4500	4500
11	3220	1304	4500	4500
12	1776	0	4500	4500
13	4000	3579	4000	4000
14	2999	1422	4000	4000
15	2000	2000	2000	2000
16	2497	2068	2500	2500
17	893	842	4000	4000
18	893	842	4000	4000

TABLE A-8. Costs

Inventory Cost	$67542900
Packaging Cost	$195976430
Transportation Cost	$84036708
Total Cost	$347556039

Reduction in capacity experiment

TABLE A-9. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	4700	4400	8000	8000
2	2000	7600	8000	8000
3	6000	3900	8000	8000
4	1900	0	5000	5000
5	2800	8000	8000	8000
6	5000	4600	8000	8000
7	3000	3300	5000	5000
8	1900	0	5000	5000
9	2800	8000	8000	8000
10	5000	4600	5000	5000
11	3000	3300	5000	5000
12	2000	1224	5000	5000

TABLE A-10. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	Day2	Day 1	Day2
1	1900	0	4800	4800
2	2800	4400	5000	5000
3	0	3600	5000	5000
4	2000	4000	4000	4000
5	3000	600	4000	4000
6	3000	3300	4000	4000
7	1900	0	5000	5000
8	2800	8000	3000	8000
9	5000	4600	6000	6000
10	3000	3300	4500	4500
11	1900	0	4500	4500
12	0	4400	4500	4500
13	2800	3600	4000	4000
14	3000	2600	4000	4000
15	2000	2000	2000	2000
16	1000	2076	1000	2500
17	2000	1224	2000	4000
18	2000	1224	4000	4000

TABLE A-11. Costs.

Inventory Cost	\$71167200
Packaging Cost	\$119211109
Transportation Cost	\$85883737
Total Cost	\$276262046

Reduction in demand experiment (50% demand)

TABLE A-12. Demand in each O-D pair

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	4230000	3520000	3830000	3150
2	2352000	1162000	1750000	1400
3	5264000	4170000	2810000	2800
4	4080000	2800000	2010000	2000
5	4248000	2520000	1710000	1800
6	2772000	3150000	4200000	3150

TABLE A-13. Flow in each path

Path number	Day 1	Day 2
1	2062	0
2	1088	0
3	0	1400
4	2800	0
5	0	0
6	0	2000
7	1800	0
8	1483	0
9	1663	0
10	4	0

TABLE A-14. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	3150	1400	8000	8000
2	2800	2000	8000	8000
3	4950	0	8000	8000
4	2062	0	5000	5000
5	3888	1400	8000	8000
6	3283	2000	8000	8000
7	1667	0	5000	5000
8	2062	0	5000	5000
9	3888	1400	8000	8000
10	3283	2000	5000	5000
11	1667	0	5000	5000
12	4	0	5000	5000

TABLE A-15. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	**Day2**	**Day 1**	**Day2**
1	2062	0	4800	4800
2	1088	1400	5000	5000
3	2800	0	5000	5000
4	0	2000	4000	4000
5	3283	0	4000	4000
6	1667	0	4000	4000
7	2062	0	5000	5000
8	3888	1400	8000	8000
9	3283	2000	6000	6000
10	1667	0	4500	4500
11	2062	0	4500	4500
12	1088	0	4500	4500
13	2800	1400	4000	4000
14	1800	0	4000	4000
15	1483	2000	2000	2000
16	1663	0	2500	2500
17	4	0	4000	4000
18	4	0	4000	4000

TABLE A-16. Costs

Inventory Cost	$32099600
Packaging Cost	$38777076
Transportation Cost	$41100878
Total Cost	$111977554

Reduction in demand experiment (60% demand)

TABLE A-17. Demand in each O-D pair

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	5076000	4224000	4596000	3780
2	2822400	1394400	2100000	1680
3	6316800	5004000	3372000	3360
4	4896000	3360000	2412000	2400
5	5097600	3024000	2052000	2160
6	3326400	3780000	5040000	3780

TABLE A-18. Flow in each path

Path number	Day 1	Day 2
1	0	0
2	0	3780
3	1680	0
4	1160	0
5	0	2200
6	600	1800
7	2160	0
8	519	0
9	2075	0
10	1186	0

TABLE A-19. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	1680	3780	8000	8000
2	1760	4000	8000	8000
3	5940	0	8000	8000
4	0	0	5000	5000
5	2840	3780	8000	8000
6	3279	4000	8000	8000
7	3261	0	5000	5000
8	0	0	5000	5000
9	2840	3780	8000	8000
10	3279	4000	5000	5000
11	3261	0	5000	5000
12	1186	0	5000	5000

TABLE A-20. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	**Day2**	**Day 1**	**Day2**
1	0	0	4800	4800
2	1680	3780	5000	5000
3	1160	0	5000	5000
4	600	4000	4000	4000
5	2679	0	4000	4000
6	3261	0	4000	4000
7	0	0	5000	5000
8	2840	3780	8000	8000
9	3279	4000	6000	6000
10	3261	0	4500	4500
11	0	0	4500	4500
12	0	3780	4500	4500
13	2840	0	4000	4000
14	2160	2200	4000	4000
15	1119	1800	2000	2000
16	2075	0	2500	2500
17	1186	0	4000	4000
18	1186	0	4000	4000

TABLE A-21. Costs

Inventory Cost	$42017800
Packaging Cost	$53086705
Transportation Cost	$50160507
Total Cost	$145265012

Reduction in demand experiment (70% demand)

TABLE A-22. Demand in each O-D pair

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	5922000	4928000	5362000	4410
2	3292800	1626800	2450000	1960
3	7369600	5838000	3934000	3920
4	5712000	3920000	2814000	2800
5	5947200	3528000	2394000	2520
6	3880800	4410000	5880000	4410

TABLE A-23. **Flow in each path**

Path number	Day 1	Day 2
1	0	0
2	0	4410
3	1960	0
4	0	2280
5	0	1640
6	2000	800
7	2520	0
8	0	409
9	2313	1
10	1687	0

TABLE A-24. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	**Day2**	**Day 1**	**Day2**
1	1960	4410	8000	8000
2	2000	4720	8000	8000
3	6520	410	8000	8000
4	0	0	5000	5000
5	1960	6690	8000	8000
6	4520	2849	8000	8000
7	4000	1	5000	5000
8	0	0	5000	5000
9	1960	6690	8000	8000
10	4520	2849	5000	5000
11	4000	1	5000	5000
12	1687	0	5000	5000

TABLE A-25. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	Day2	Day 1	Day2
1	0	0	4800	4800
2	1960	4410	5000	5000
3	0	2280	5000	5000
4	2000	2440	4000	4000
5	2520	409	4000	4000
6	4000	1	4000	4000
7	0	0	5000	5000
8	1960	6690	8000	8000
9	4520	2849	6000	6000
10	4000	1	4500	4500
11	0	0	4500	4500
12	0	4410	4500	4500
13	1960	2280	4000	4000
14	2520	1640	4000	4000
15	2000	1209	2000	2000
16	2313	1	2500	2500
17	1687	0	4000	4000
18	1687	0	4000	4000

TABLE A-26. Costs

Inventory Cost	$49019500
Packaging Cost	$62870368
Transportation Cost	$59341871
Total Cost	$145265012

Reduction in demand experiment (80% demand)

TABLE A-27. Demand in each O-D pair

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	6768000	5632000	6128000	5040
2	3763200	1859200	2800000	2240
3	8422400	6672000	4496000	4480
4	6528000	4480000	3216000	3200
5	6796800	4032000	2736000	2880
6	4435200	5040000	6720000	5040

TABLE A-28. **Flow in each path**

Path number	Day 1	Day 2
1	540	0
2	0	4500
3	2240	0
4	0	2633
5	0	1847
6	2000	1200
7	2880	0
8	0	136
9	2498	904
10	1502	0

TABLE A-29. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	**Day2**	**Day 1**	**Day2**
1	2780	4500	8000	8000
2	2000	5680	8000	8000
3	6880	1040	8000	8000
4	540	0	5000	5000
5	2240	7133	8000	8000
6	4880	3183	8000	8000
7	4000	904	5000	5000
8	540	0	5000	5000
9	2240	7133	8000	8000
10	4880	3183	5000	5000
11	4000	904	5000	5000
12	1502	0	5000	5000

TABLE A-30. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	Day2	Day 1	Day2
1	540	0	4800	4800
2	2240	4500	5000	5000
3	0	2633	5000	5000
4	2000	3047	4000	4000
5	2880	136	4000	4000
6	4000	904	4000	4000
7	540	0	5000	5000
8	2240	7133	8000	8000
9	4880	3183	6000	6000
10	4000	904	4500	4500
11	540	0	4500	4500
12	0	4500	4500	4500
13	2240	2633	4000	4000
14	2880	1847	4000	4000
15	2000	1336	2000	2000
16	2498	904	2500	2500
17	1502	0	4000	4000
18	1502	0	4000	4000

TABLE A-31. Costs

Inventory Cost	$55962500
Packaging Cost	$78278341
Transportation Cost	$68089386
Total Cost	$202330227

Reduction in demand experiment (90% demand)

TABLE A-32. Demand in each O-D pair

Number of O-D pair	Small Box (216 x 119 x 41 mm)	Medium Box (216 x 119 x 76 mm)	Large Box (241x221x114 mm)	Number of trucks
1	7614000	6336000	6894000	5670
2	4233600	2091600	3150000	2520
3	9475200	7506000	5058000	5040
4	7344000	5040000	3618000	3600
5	7646400	4536000	3078000	3240
6	4989600	5670000	7560000	5670

TABLE A-33. Flow in each path

Path number	Day 1	Day 2
1	1170	0
2	0	4500
3	2520	0
4	0	3137
5	0	1903
6	1957	1643
7	3043	197
8	0	0
9	2489	1670
10	1511	0

TABLE A-34. Flow and capacity of centers.

Center Num	Flow in Centers		Capacity of Centers	
	Day1	Day2	Day 1	Day2
1	3690	4500	8000	8000
2	1957	6683	8000	8000
3	7043	1867	8000	8000
4	1170	0	5000	5000
5	2520	7637	8000	8000
6	5000	3743	8000	8000
7	4000	1670	5000	5000
8	1170	0	5000	5000
9	2520	7637	8000	8000
10	5000	3743	5000	5000
11	4000	1670	5000	5000
12	1511	0	5000	5000

TABLE A-35. Flow and capacity of links.

Link Num	Link Flow		Capacity of Links	
	Day1	Day2	Day 1	Day2
1	1170	0	4800	4800
2	2520	4500	5000	5000
3	0	3137	5000	5000
4	1957	3546	4000	4000
5	3043	197	4000	4000
6	4000	1670	4000	4000
7	1170	0	5000	5000
8	2520	7637	8000	8000
9	5000	3743	6000	6000
10	4000	1670	4500	4500
11	1170	0	4500	4500
12	0	4500	4500	4500
13	2520	3137	4000	4000
14	3043	2100	4000	4000
15	1957	1643	2000	2000
16	2489	1670	2500	2500
17	1511	0	4000	4000
18	1511	0	4000	4000

TABLE A-36. Costs

Inventory Cost	$63001500
Packaging Cost	$95933357
Transportation Cost	$76874808
Total Cost	$235809664