DETERMINING TRANSPORTATION MODE CHOICE TO MINIMIZE DISTRIBUTION COST: DIRECT SHIPPING, TRANSIT POINT AND 2-ROUTING

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ABSTRACT

We consider a problem in which a supplier must determine the transportation mode for product deliveries to satisfy demand from a set of retailers. Based on combinations of four possible transportation modes, we consider seven different distribution policies on set of instances derived from data from an Italian company. For three demand scenarios (low, moderate, high), we compare the performance of the various distribution policies. Based on demand characteristics, we characterize the optimal distribution policies. We demonstrate the increase in cost resulting from restricting mode choice to a subset of the possibilities.

INTRODUCTION

Motivated by a situation faced by an Italian company, we consider a problem in which a supplier must determine the transportation mode for product deliveries to a set of retailers. Each retailer's daily demand is known and measured in pallets. The objective is to minimize the overall cost of satisfying retailer demand. For each retailer shipment, the supplier has the choice of four possible transportation modes: *Vehicles*, *Pallets*, *Transit*, *2-Route*. In the *Vehicles* mode, the supplier directly serves a retailer by using a dedicated set of vehicles and pays a fixed cost for each vehicle. In the *Pallets* mode, the supplier directly serves a retailer, but does not reserve the entire vehicle. Instead, the supplier pays a per-pallet transportation cost defined by tiered echelon pricing. The *Transit* mode utilizes a transit point and combines elements of the *Vehicles* and *Pallets* mode. The supplier consolidates the demand intended for a specified set of retailers and uses a dedicated set of vehicles, incurring a fixed cost per vehicle, to deliver this consolidated demand to a transit point. The supplier then pays a per-pallet transportation cost, defined by tiered echelon pricing, to directly deliver each individual retailer's demand from the transit point. Finally, in the *2-Route* mode, the supplier specifies a pair of retailers and serves them with a route that begins and ends at the supplier, incurring a fixed cost for each vehicle.

In this paper, we compare a variety of distribution polices characterized by the allowed modes. Specifically, we study the following seven policies:
1) *Direct Shipping (D)*: Each retailer is directly served using the modes *Vehicles (V)* or *Pallets (P)*;
2) *Transit Point (TP)*: Each retailers is served through the transit point using the *Transit* mode;
3) *2-Routing (2R)*: Each retailer is served by using either the *Vehicles* or *2-Route* mode (we use a cost structure such that serving a retailer via the *Vehicles* mode is equivalent to serving a retailer via the *2-Route* mode without another paired retailer);
4) *D+TP*: Each retailer is served by using the *Vehicles*, *Pallets* or *Transit* mode;
5) *D+2R*: Each retailer is served by using the *Vehicles*, *Pallets* or *2-Route* mode;
6) *TP+2R*: Each retailer is served by using the *Transit*, *Vehicles* or *2-Route* mode;
7) *D+TP+2R*: Each retailer is served by using the *Vehicles*, *Pallets*, *Transit* or *2-Route* mode.

The contribution of this paper is the formulation and application of a series of integer optimization models to compare seven different distribution policies using four possible transportation modes. Specifically, our computational experiments examine the impact of demand level on the distribution policy.

LITERATURE REVIEW

The literature containing elements of transportation mode choice is vast and includes surveys, case studies, and mathematical models. We focus on the most related mathematical treatments of transportation mode choice. For a general survey documenting industry challenges, we refer the reader to Meixell and Norbis (2008).

There is a thread of research which incorporates vehicle routing with mode choice (typically a choice between delivery on routes executed by an internal fleet or delivery via an external carrier). Due to the complexity of the resulting problem (an enriched vehicle routing

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problem), this work has focused on the development of heuristic approaches. Côté and Potvin (2009) and Potvin and Naud (2011) are recent works along this meme.

The vehicle routing literature also includes models that incorporate a cross-dock, a type of transit point where loads can be consolidated or separated. Representative work in this area includes Wen et al. (2009) and Tarantilis (2013). These models are concerned with sequencing the loads and the dependencies between the vehicles arriving to and departing from the cross-dock. Due to the complexity of the problem, most studies focus on the development of heuristics.

In contrast to the vehicle routing literature containing elements of mode choice and transit point, our analysis is not saddled with load sequencing decisions. Rather, by our design of the available mode choices, we can focus the impact of demand characteristics on mode selection.

The study of mode choice is also prominent in the inventory literature. Kiesmuller et al. (2005) consider a class of order-up-to policies and compute the optimal policy parameters in the presence of two supply modes. Chiang (2013) considers periodic review inventory policies and computes the optimal policy parameters in the case with two supply modes. In this paper, we are concerned with specifying transportation mode given daily demands from a set of retailers and do not consider the inventory policies of the retailers.

The effect of mode on shipment size has also been examined. Hall (1985) considers a single supplier and single customer to simultaneously determine the optimal mode and shipment size. In related work, Archetti et al. (2011) study lot-sizing in the presence of a transportation cost based on tiered echelons. Our work differs from this thread as we assume demand for our set of suppliers is exogeneous and shipment sizes must satisfy demand.

FORMAL PROBLEM DESCRIPTION

We consider a set $I = \{1,2,...,|I|\}$ of retailers where each retailer $i \in I$ is located at (X_i, Y_i) and has a known daily demand of d_i pallets. The supplier 0 is located at (X_0, Y_0) and a transit point *TP* is located at (X_{TP}, Y_{TP}). The supplier can transport the demand of each retailer $i \in I$ via four modes: *Vehicles*, *Pallets*, *Transit* and *2-Route*. The problem is to determine the transportation mode for each retailer $i \in I$ that minimizes the overall transportation cost of satisfying all retailer demand.

In the *Vehicles* mode, a set $J^V = \{1,2,...,|J^V|\}$ of different types of vehicles is available. Each vehicle type $j \in J^V$ has capacity of r_j^V pallets and incurs a fixed cost c_{ij}^V for each shipment from the supplier to the retailer i.

In the *Pallets* mode, the cost structure is defined by a set $Q^P = \{1,2,...,|Q^P|\}$ of echelons. Each echelon $q \in Q^P$ is defined by a minimum p_q^P and a maximum P_q^P number of pallets and implies a per-pallet transportation cost f_{iq}^P. For $q = 1,2,...,|Q^P|-1$, $f_{iq}^P > f_{iq+1}^P$, i.e., the unit cost of each echelon is greater than the unit cost of the next echelon.

In the *Transit* mode, shipment from the supplier to a retailer is broken into two stages. In the first stage, the supplier consolidates shipments for a specified set of retailers and ships the products to the transit point *TP* on vehicles shared with other retailers. Each vehicle type $j \in J^{TP} = \{1,2,...,|J^{TP}|\}$ has capacity of r_j^{TP} pallets and incurs a fixed cost c_j^{TP} for each journey from the supplier to the transit point. In the second stage of delivery, the shipment from the transit point to each retailer $i \in I$ is based on per-pallet transportation costs defined by a set $Q^{TP} = \{1,2,...,|Q^{TP}|\}$ of echelons. Each echelon $q \in Q^{TP}$ is characterized by a minimum p_q^{TP} and a maximum P_q^{TP} number of pallets and by per-pallet transportation cost f_{iq}^{TP}. For $q = 1,2,...,|Q^{TP}|-1$, $f_{iq}^{TP} > f_{iq+1}^{TP}$.

In the *2-Route* mode, the retailer i is served together with another retailer s by using the vehicles $j \in J^{2R} = \{1,2,...,|J^{2R}|\}$ to travel routes starting at the supplier, visiting the two retailers and going back to the supplier. Each vehicle $j \in J^{2R}$ has capacity r_j^{2R}. We denote by c_{isj}^{2R} the cost to serve the retailers i and s together by using one vehicle of type $j \in J^{2R}$.

DIRECT SHIPPING FORMULATION

In the *Direct Shipping* policy, each retailer $i \in I$ is served by using either the *Vehicles* mode or the *Pallets* mode. Let x_i^V be a binary variable equal to 1 if *Vehicles* is used and 0 otherwise, and v_{ij}^D be a non-negative integer variable representing the number of vehicles of type $j \in J^V$ used to serve i. Let x_i^P be a binary variable equal to 1 if *Pallets* is used and 0 otherwise, and z_{iq}^P be a binary variable equal to 1 if echelon q corresponds to the demand d_i and 0 otherwise. Finally, let M be a sufficiently large number. Then, the optimal

Direct Shipping policy can be obtained by solving the following model:

$$\min \sum_{i\in I}\sum_{j\in J^V} c_{ij}^V v_{ij}^V + \sum_{i\in I}\sum_{q\in Q^P} d_i f_{iq}^P z_{iq}^P \tag{1}$$

$$x_i^V + x_i^P = 1 \quad i\in I \tag{2}$$

$$d_i x_i^V \le \sum_{j\in J^V} r_j^V v_{ij}^V \quad i\in I \tag{3}$$

$$\sum_{q\in Q^P} z_{iq}^P = x_i^P \quad i\in I \tag{4}$$

$$d_i x_i^P \ge p_q^P z_{iq}^P - M(1-z_{iq}^P) \quad q\in Q^P \quad i\in I \tag{5}$$

$$d_i x_i^P \le P_q^P z_{iq}^P + M(1-z_{iq}^P) \quad q\in Q^P \quad i\in I \tag{6}$$

$$v_{ij}^V \ge 0 \text{ integer} \quad j\in J^V \quad i\in I \tag{7}$$

$$z_{iq}^P \in \{0,1\} \quad q\in Q^P \quad i\in I \tag{8}$$

$$x_i^V \in \{0,1\} \quad i\in I \tag{9}$$

$$x_i^P \in \{0,1\} \quad i\in I \tag{10}$$

The objective function (1) expresses the minimization of the sum of the cost of the *Vehicles* and *Pallets* modes. Constraints (2) guarantee that exactly one mode is selected for each retailer i. Constraints (3) guarantee that, in the case *Vehicles* is selected, the total number of vehicles used is sufficient to send the demand d_i. Constraints (4)-(6) manage the *Pallets* mode. In particular, constraints (4) guarantee that at most one echelon is selected. Constraints (5)-(6) specify that the selected echelon q is such that the demand d_i is not lower than the minimum number of pallets and not greater than the maximum number of pallets of the selected echelon. Finally, (7)-(10) define the decision variables of the problem. Note that this problem can be decomposed into $|I|$ problems, one for each retailer $i\in I$.

TRANSIT POINT FORMULATION

In the *Transit Point* policy, first the pallets of several retailers are consolidated and sent to the transit point TP and then they are sent from the transit point to each retailer, separately, on the basis of echelon costs. Let v_j^{TP} be a non-negative integer variable representing the number of vehicles of type $j\in J^{TP}$ used to send the products from the supplier to the transit point and z_{iq}^{TP} be a binary variable equal to 1 if the echelon q corresponds to the demand d_i of retailer $i\in I$ and 0 otherwise. Then, the optimal *Transit Point* policy can be obtained by solving the following model:

$$\min \sum_{j\in J^{TP}} c_j^{TP} v_j^{TP} + \sum_{i\in I}\sum_{q\in Q^{TP}} d_i f_{iq}^{TP} z_{iq}^{TP} \tag{11}$$

$$\sum_{j\in J^{TP}} r_j^{TP} v_j^{TP} \ge \sum_{i\in I} d_i \tag{12}$$

$$\sum_{q\in Q^{TP}} z_{iq}^{TP} = 1 \quad i\in I \tag{13}$$

$$p_q^{TP} z_{iq}^{TP} - M(1-z_{iq}^{TP}) \le d_i \quad i\in I \quad q\in Q^{TP} \tag{14}$$

$$P_q^{TP} z_{iq}^{TP} + M(1-z_{iq}^{TP}) \ge d_i \quad i\in I \quad q\in Q^{TP} \tag{15}$$

$$v_j^{TP} \ge 0 \quad \text{integer} \quad j\in J^{TP} \tag{16}$$

$$z_{iq}^{TP} \in \{0,1\} \quad i\in I \quad q\in Q^{TP} \tag{17}$$

The objective function (11) expresses the minimization of the sum of the transportation cost from the supplier to the transit point and the transportation cost from the transit point to the retailers. Constraints (12) guarantee that the total number of vehicles used from the supplier to the transit point is sufficient to send the total demand. Constraints (13)-(15) concern the transportation from the transit point to the retailers. In particular, Constraints (13) guarantee that only one echelon is selected for each retailer, while Constraints (14)-(15) guarantee that the echelon selected for each retailer $i\in I$ is such that the demand d_i is not lower than the minimum number of pallets and not greater than the maximum number of pallets of the selected echelon. Finally, Constraints (16)-(17) define the decision variables of the problem.

2-ROUTING FORMULATION

In the *2-Routing* policy, each retailer $i\in I$ is either served directly by using the *Vehicles* mode or together with another customer $s\in I$ on a route starting at the supplier, visiting the two customers and returning to the supplier. We define v_{isj}^{2R} a non-negative integer variable representing the number of vehicles of type $j\in J^{2R}$ used to jointly serve i and s and y_{is}^{2R} a binary variable equal to 1 if the retailers i and s are served together and 0 otherwise. We define δ_{isj}^{2R} equal to $0.5c_{isj}^{2R}$ when $i\ne s$ and equal to $c_{iij}^{2R} = c_{ij}^{v}$ otherwise. Then, the optimal *2-Routing* policy can be obtained by solving the following model:

$$\min \sum_{i\in I}\sum_{s\in I}\sum_{j\in J^{2R}} \delta_{isj}^{2R} v_{isj}^{2R} \tag{18}$$

$$(d_i + d_s) y_{is}^{2R} \le \sum_{j\in J^{2R}} r_j^{2R} v_{isj}^{2R} \quad i\in I \quad s\in I, i\ne s \tag{19}$$

$$d_i y_{ii}^{2R} \le \sum_{j\in J^{2R}} r_j^{2R} v_{iij}^{2R} \quad i\in I \tag{20}$$

$$\sum_{s\in I} y_{is}^{2R} = 1 \quad i\in I \tag{21}$$

$$y_{is}^{2R} = y_{si}^{2R} \quad i\in I \quad s\in I \tag{22}$$

$$v_{isj}^{2R} \ge 0 \quad \text{integer} \quad i\in I \quad s\in I \quad j\in J^{2R} \tag{23}$$

$$y_{is}^{2R} \in \{0,1\} \quad i\in I \quad s\in I \tag{24}$$

The objective function (18) expresses the minimization of the transportation cost for serving one or two retailers in every journey. Constraints (19) guarantee that, if the retailers i and s are served together, then the total transportation capacity is sufficient to load the total demand $d_i + d_s$. Constraints (20) guarantee that, if only the retailer i is served on a journey, then the total transportation capacity is sufficient to load the demand d_i. Constraints (21) guarantee that either each retailer is served directly or together with another retailer. Constraints (22) guarantee that if i is served together with s, then s is served together with i. Finally, Constraints (23)-(24) define the decision variables of the problem.

FORMULATIONS OF INTEGRATED POLICIES

We now combine the previous three models to obtain the integrated policies *D+TP*, *D+2R*, *TP+2R* and *D+TP+2R*. We first formulate the model for the latter policy and then we obtain the others by solving particular cases of this model. Let x_i^{TP} be a binary variable equal to 1 if the retailer $i \in I$ is served by applying the transportation mode *Transit* and 0 otherwise.
Then, the optimal *D+TP+2R* policy can be obtained by solving the following model:

$$\min \sum_{i\in I}\sum_{j\in J^V} c_{ij}^V v_{ij}^V + \sum_{i\in I}\sum_{q\in Q^P} d_i f_{iq}^P z_{iq}^P + \sum_{j\in J^{TP}} c_j^{TP} v_j^{TP} + \sum_{i\in I}\sum_{q\in Q^{TP}} d_i f_{iq}^{TP} z_{iq}^{TP} + \sum_{i\in I}\sum_{s\in I}\sum_{j\in J^{2R}} \delta_{isj}^{2R} v_{isj}^{2R} \tag{24}$$

$$x_i^V + x_i^P + x_i^{TP} + \sum_{s\in I} y_{is}^{2R} = 1 \quad i \in I \tag{25}$$

(3)-(10)

(14)-(17)

$$\sum_{j\in J^{TP}} r_j^{TP} v_j^{TP} \ge \sum_{i\in I} d_i x_i^{TP} \tag{26}$$

$$\sum_{q\in Q^{TP}} z_{iq}^{TP} = x_i^{TP} \quad i \in I \tag{27}$$

$$x_i^{TP} \in \{0,1\} \quad i \in I \tag{28}$$

(19)-(24)

The objective function (24) is given by the sum of the objective functions of the previous models. Constraints (25) guarantee that for each retailer $i \in I$ exactly one transportation mode is selected. Constraints (3)-(10) are the constraints of the *Vehicles* and *Pallets* modes. Constraints (14)-(17) and (26)-(28) are the constraints of the *Transit* mode. Finally, Constraints (19)-(24) are the constraints of the *2-Route* mode. We use this model to also obtain the following integrated policies:

1) *Direct* + *Transit Point* (*D+TP*) by setting $y_{is}^{2R} = 0$ for all i and s;

2) *Direct* + *2-Routing* (*D+2R*) by setting $x_i^{TP} = 0$ for all i;

3) *Transit Point* + *2-Routing* (*TP+2R*) by setting $x_i^V = x_i^P = 0$ for all i.

COMPUTATIONAL RESULTS

We generate realistic problem instances based on data from a primary Italian company. In the *Vehicles* mode, there are two different types of vehicles available at the supplier, i.e., $|J^V| = 2$. The first vehicle type has pallet capacity $r_1^V = 20$ while the second has pallet capacity $r_2^V = 34$. The cost structure for the *Vehicles* mode is set so the fixed costs c_{i1}^V is equal to twice the Euclidean distance of customer i from the supplier, while $c_{i2}^V = 1.5c_{i1}^V$.

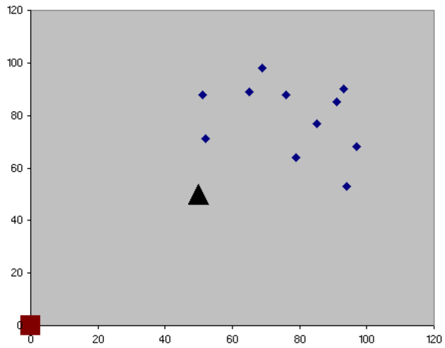
In the *Pallets* mode, there is a set Q^P of four echelons. Each echelon q is defined by a range $[p_q^P, P_q^P]$ for which the echelon pricing is effective. The four echelon ranges are: [1,10]; [11,15]; [16,20]; [21, ∞). The corresponding per-pallet cost f_{iq}^P is defined such that the cost of one pallet in the fourth echelon is 20% more than $c_{i1}^V / 20$ and the per-pallet cost of each echelon q is 20% more than the per-pallet cost of the echelon $q+1$, for $q = 1,2,3$.

In the *Transit* mode, there are two types of vehicles $\left(|J^{TP}| = 2\right)$ with pallet capacity $r_1^{TP} = 20$ and $r_2^{TP} = 34$, handling the transportation from the supplier to the transit point. The first vehicle type's fixed cost c_1^{TP} is equal to two times the Euclidean distance between the supplier and the transit point. For the second vehicle type, the fixed cost is $c_2^{TP} = 1.5c_1^{TP}$. A set Q^{TP} of four echelons exists for shipments from the transit point to the retailers. Each echelon q is defined by a range $[p_q^{TP}, P_q^{TP}]$ for which the echelon pricing is effective. The four echelon ranges are: [1,4]; [5,10]; [11,20]; [21, ∞). The corresponding per-pallet cost f_{iq}^{TP} is defined such that the cost of one pallet in the fourth echelon is 20% more than $(c_{i1}^V - c_1^{TP})/20$ and the per-pallet cost of each echelon q is 20% more than the per-pallet cost of the echelon $q+1$, for $q = 1,2,3$.

In the *2-Route* mode, two types of vehicles, $|J^{2R}| = 2$, with pallet capacity $r_1^{2R} = 20$ and $r_2^{2R} = 34$. For the first vehicle type, the cost c_{is1}^{2R} to serve retailers i and s together is equal to the total Euclidean distance of the minimum-length Hamiltonian circuit on the supplier, retailer i, and retailer s. For the second vehicle type, $c_{is2}^{2R} = 1.5c_{is1}^{2R}$.

As shown in Figure 1, the supplier, located in (0,0), serves a set I of 11 retailers, randomly generated in the square having south-west corner in (50,50) and edge of length 50. The transit point is located in (50,50).

Figure 1: Location of the supplier (square), of the transit point (triangle) and of the retailers (rhombuses)



We generate the daily demand d_i for each retailer i as follows. First, a random number $0 \le \alpha_i \le 1$ is generated from a uniform distribution. If $\alpha_i \le 0.5$, then $d_i = 0$; otherwise, d_i is randomly generated from a uniform distribution between a minimum $\underline{d}$ and a maximum $\overline{d}$ number of pallets. We repeat this process for each day of the 24-day horizon so that each day consist of $|I|$ randomly-generate demand values.

We construct demand scenarios by varying the minimum and maximum number of pallets possible:

1) *Low demand:* $\underline{d} = 5, \overline{d} = 5$.
2) *Moderate demand:* $\underline{d} = 5, \overline{d} = 34$.
3) *High demand:* $\underline{d} = 34, \overline{d} = 34$.

For each scenario, we generate five instances and we apply the policies *Direct Shipping* (*D*), *Transit Point* (*TP*), *2-Routing* (*2R*), *D+TP*, *D+2R*, *TP+2R* and *D+TP+2R* by solving the corresponding formulation for each day in the 24-day horizon. We implement the models formulated in the previous sections in MPL (Maximal Software 2013) and apply Gurobi (Gurobi Optimization 2013), a mathematical programming solver, to obtain the corresponding optimal solutions.

Table 1 shows the average percentage error increase in the transportation cost obtained by the policies *D*, *TP*, *2R*, *D+TP*, *D+2R*, *TP+2R* with respect to the policy *D+TP+2R*, in the three scenarios. In the low demand scenarios the use of the transit point can significantly reduce the transportation cost with respect to direct shipping and 2-routing. In fact, the policies *TP*, *D+TP* and *TP+2R* give the same cost of the policy *D+TP+2R*, while *D* has an increase in the cost of about 54% and 2R of about 71%. In the high demand scenarios, the use of direct shipping and 2-routing give the optimal cost, while the use of the transit point implies an increase in the cost of about 14%. In the case with moderate demand, a right combination of the different transportation modes is needed to have the minimum cost. In fact, the policy *D*, *TP* and *2R* give an increase in the cost of *D+TP+2R* of about 19%, 5% and 4%, respectively. However, if these policies are integrated, the increase is substantially reduced: It is about 2% for *D+TP*, about 3.5% for *D+2R* and about 0.16% for *TP+2R*. Note that even the best of these policies is not able to give the cost of *D+TP+2R*. Therefore, the four transportation modes are needed to obtain the best policy.

Table 1. Performance of the Policies with Respect to *D+TP+2R*

Policy\ Scenario	Low Demand	Moderate Demand	High Demand
D	53.71	19.11	0.00
TP	0.00	4.96	14.09
2R	70.99	3.88	0.00
D+TP	0.00	1.99	0.00
D+2R	53.68	3.49	0.00
TP+2R	0.00	0.16	0.00

Table 2 illustrates how the different transportation modes (*Vehicles*, *Pallets*, *Transit* and *2-Route*) are used in the optimal solution of *D+TP+2R*. In the case of low demand, all retailers are served via transit point. In the case of high demand, all retailers are served by direct shipping. In the case of moderate demand, all transportation modes are used; about 49% of the retailers are served via transit point, about 29% are served via 2-routing, about 19% are served with dedicated vehicles, and about 3% are served directly with echelon-based costs.

Table 2. Transportation Modes Used in the Optimal Policy *D+TP+2R*

Policy\ Scenario	Low Demand	Moderate Demand	High Demand
Vehicles	0.00	19.43	100.00
Pallets	0.00	2.67	0.00
Transit	100.00	48.57	0.00
2-Route	0.00	29.33	0.00

CONCLUSION

We investigate the problem of determining transportation mode for deliveries from a single supplier to multiple retailers. We present a series of mathematical formulations to determine the optimal selection of transportation mode from four choices: 1) direct, dedicated delivery with fixed vehicle costs, 2) direct delivery with volume-based costs defined by echelon-based pricing, 3) delivery via a transit point, 4) delivery via routes consisting of pairs of suppliers.

Our computational results suggest that optimal mode choice is highly sensitive to level of demand. At low demand levels, the use of a transit point allowing consolidation is crucial to obtaining a low-cost solution. In contrast, high demand levels facilitate the use of direct shipping and forcing the use of a transit point causes a 14% increase in cost. Moderate demand levels result in the utilization of all four transportation modes, but restricting the modes to only using a transit point or routing pairs of suppliers results in only a 0.16% increase in cost. Future work could explore the utility of these observations in a solution approach for identifying near-optimal distribution strategies in a large network of retailers for which consideration of all possible modes for the entire set of retailers may be intractable.

In this paper, we consider daily mode assignment in which the transportation mode for each retailer is re-optimized each day from the available choices. Depending on the available mode choices, this may result in a retailer's mode changing day-to-day. Future work may consider incorporating the cost of switching a retailer's mode or fixing a retailer's mode over the planning horizon.

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