EFFECTS OF TRANSPORTATION COST AND LEAD-TIME ON SELECTING MULTIPLE SUPPLIERS

by

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ABSTRACT

Supplier selection aims at determining two common decisions, namely, which suppliers should be selected and how much of any particular order should be split among them. To do so involves many criteria, factors and conditions. One significant factor is transportation cost and its relationship to other parameters, and in particular, inventory cost and lead-time. A model that includes transportation cost is presented. The objective function is to minimize total cost, comprising purchasing, inventory and transportation. Computational results show that transportation cost has a significant impact on the decisions. To determine the optimal order quantity, it has to be traded off with inventory cost, because they conflict. In addition, lead-time can allow inventory cost reduction if the selected suppliers have different lead-times. Application of the proposed model can offer transportation and total cost saving in supplier selection.

KEYWORDS
Supplier Selection, Transportation Cost, Inventory Cost

INTRODUCTION

In ordering stock, a purchasing department selects suitable suppliers and decides the proportion of the order to allocate to each. The buyer may assign the order either to a single supplier or to multiple suppliers. A single supplier must be able to meet all conditions—such as capacity, quality and delivery time—without qualification. If a single supplier cannot handle the entire order—because it cannot adequately meet all requirements for the order—then the buyer splits the order among multiple suppliers. Moreover, the buyer may be able to reduce inventory by splitting the order among suppliers with different delivery lead-times.

Various criteria can be applied to evaluate potential suppliers. Dickson (1966) extracted twenty-three criteria from the results of a questionnaire he sent to purchasing agents and managers. He found that quality was the most important criterion, followed by delivery. Using Dickson’s criteria, Weber, Current and Benton (1991) reviewed 74 academic papers published in major journals written in English. They found that net price was the most common criterion discussed in 80% of papers. Delivery and quality were ranked second and third by 58% and 53% of papers, respectively. Both surveys found delivery was an important criterion; practitioners and academic authors equally ranked it. Liu and Hai (2005) also found delivery a significant criterion for practitioners. They developed a variant of Saaty’s Analytic Hierarchy Process (AHP), which they called Voting AHP, in which managers and supervisors vote to rank criteria. In a case study of a furniture company, a third of voters voted delivery as the top priority out of a field of 8 criteria and 13 subcriteria.

From an operation’s research perspective, supplier selection is a multiple objective problem. While total cost is prevalent in objective functions presented in the literature, the constituents of total cost vary. For example, Ghodsypour and O’Brien’s (2001) non-linear integer programming model for selecting suppliers, total cost comprises aggregate price, ordering and inventory cost. Liao and Rittscher (2007) developed a supplier selection model associated with three objectives: total rejected items due to quality, total late deliveries, and total cost. Here, total cost includes purchasing, ordering, inventory holding, shipping and in-transit holding cost.

Most papers on supplier selection focus solely on purchasing and inventory cost, and ignore transportation cost: a significant contributor to total cost as explained by Aguezzoul and Ladet (2007), Thomas and Tyworth (2006), and Tyworth and Ruiz-Torres (2000). Ghodsypour and O’Brien (2001) state that transportation cost is important and refer in the conclusion of their paper that total cost in their model includes transportation, inspection, ordering and storage costs.
However, their model does not express any of these costs explicitly. Tyworth and Ruiz-Torres (2000) studied the effect of transportation cost on sole and dual sourcing. They found that transportation costs could greatly affect choosing between single and dual sources. An outcome of the tradeoff between transportation cost and inventory costs and the structure of freight costs that cause higher costs in splitting orders. Kreng and Wang (2005) proposed a model in which the total cost included transportation as a function of delivery time for different modes of transport. However, constraints and optimization techniques are not discussed. In studying multiple-supplier selection, Aguezzoul and Ladet (2007) included transportation cost within total cost. Transportation cost was based on two factors: distance between suppliers and the buyer and whether the trucks were fully laden.

Transportation cost may be significant and can contribute to high total cost of the buyer. In addition, it affects other factors, in particular inventory cost. In this paper, we propose a model for multiple-supplier selection that includes transportation cost. The objective of the model is to split orders among selected suppliers to minimize total cost, comprising purchasing, ordering, holding and transportation costs.

ASSUMPTIONS AND NOTATIONS FOR THE MODEL

As consideration of all potential factors and conditions that could arise in purchasing makes it extremely complicated and difficult to formulate a model, the following some assumptions were made.

- Demand is known and constant over time and only one product type is considered
- Each supplier might quote different prices for the same product
- Each supplier has a limited capacity
- The order is placed simultaneously to all selected suppliers
- Unit price of an order is invariant of order quantity
- Delivery lead-time from each supplier is known and constant
- In-transit holding cost is not considered and no shortages are allowed
- Production time of both buyer and suppliers is not considered
- Capacity for transportation of each supplier is unlimited
- Budgeting for the buyer is unlimited

Notations of this paper are defined as follow.

**Index:**

- \( i \) = The index indicator for suppliers, \( i = 1, \ldots, n \)

**Parameters:**

- \( P_i \) = Unit product price from supplier \( i \) ($)
- \( P_{rc} \) = Total purchasing cost ($)
- \( F_i \) = Fixed transportation cost charged by supplier \( i \) ($)
- \( V_i \) = Variable transportation cost from supplier \( i \) ($)
- \( Trs \) = Total transportation cost ($)
- \( A_i \) = Ordering cost for placing each order to supplier \( i \) ($)
- \( Inv \) = Total inventory cost ($)
- \( h \) = holding rate
- \( I_{avg} \) = The average inventory level (unit)
- \( D \) = Annual demand that is known and constant (units)
- \( d \) = Daily demand rate that is constant per unit time (units)
- \( l_i \) = Lead-time (or delivery lead-time) from supplier \( i \) (days)
- \( c_i \) = Capacity of supplier \( i \) (units)
- \( C_{total} \) = Total cost ($)

**Decision variables**

- \( Q \) = Order quantity
- \( X_i \) = A proportion of total order quantity split to supplier \( i \); \( 0 \leq X_i \leq 1 \)
- \( \lambda_i \) = 1 if supplier \( i \) is selected, \((X_i \neq 0) \) 0 otherwise
MODEL DEVELOPMENT

The model is based on the buyer being responsible for transportation cost due to purchasing goods on an FOB (free onboard) basis. Therefore, the buyer includes transportation cost explicitly in the total cost. It accounts for limited capacity of suppliers. The model aims at minimizing total cost associated with purchasing, inventory and transportation cost, each of which is detailed as follows.

1. Purchasing cost \( (Prc) \) is derived from summing the price from each supplier multiplied by proportion of total demand quantity split to each supplier.

\[
Prc = \sum_{i=1}^{n} D_i P_i X_i
\]  

2. Transportation cost \((Trs)\) has two components: total fixed and variable costs. Total fixed cost depends on the number of deliveries and fixed cost for each delivery. While total variable cost is calculated from proportion of total demand quantity allocated to each supplier multiplies by variable cost rate that is charged as total weight of order.

Total fixed cost

\[
= \frac{\sum_{i=1}^{n} D_i F_i \lambda_i}{Q}
\]

Total variable cost

\[
= \frac{D}{Q} \sum_{i=1}^{n} Q_i X_i = \sum_{i=1}^{n} D_i X_i
\]

Therefore, \( Trs = D \sum_{i=1}^{n} \left( \frac{F_i A_i}{Q} + V_i X_i \right) \)

3. Inventory cost \((Inv)\) equals total ordering cost plus total holding cost.

\[
Inv = \frac{D}{Q} \sum_{i=1}^{n} A_i \lambda_i + \sum_{i=1}^{n} h_i P_i I_{avg}
\]

The first term is ordering cost, which depends on the total number of orders. The second term is holding cost, which can be calculated from the average inventory holding level \((I_{avg})\) described in Section 3.1, multiplied by holding cost per item \((h_i P_i)\), which is normally charged as a proportion of the product’s price.

THE AVERAGE LEVEL OF INVENTORY \((I_{avg})\)

The average inventory level denotes the holding inventory for the replenishment period. It affects the amount of capital spent directly on inventory and on related facilities such as warehouse space, operators and equipment. The inventory system for this paper, shown in Figure 1, extends the representation for two suppliers by Lau and Zhao (1993). In Figure 1, for multiple supplier or order splitting, when the inventory level is depleted to the reorder point \((R)\), the entire order is split and placed simultaneously with all selected suppliers, who may offer different delivery times.

FIGURE 1
INVENTORY SYSTEM
In general, $Q_i$ is the inventory level after the order from the $i^{th}$ supplier arrives. Therefore, the average inventory is the sum of all trapezoid areas ($I_{i-1}I_{i+1}$) under the inventory curve divided by the replenishment cycle time, $T$. Thus, in comparing to inventory of single supplier (level $Q$), it can be seen that splitting order can allow inventory reduction, shown as shaded area in Figure 1. That is:

$$I_{avg} = \frac{I_1 + I_2 + \cdots + I_{n+1}}{T}, \quad T = \frac{Q}{d}$$

(6)

Hence, average inventory level for multiple suppliers is:

$$I_{avg} = \frac{1}{2} \sum_{i=1}^{n} \frac{X_i Q_i}{2} - \sum_{i=1}^{n} dX_i \left( l_i - \arg \min l_i \right)$$

(7)

### 3.2 The objective function

From all cost components, described previously at the beginning of Section 3, the total cost equation can be summarized below.

$$C_{total} = \sum_{i=1}^{n} D P X_i + \sum_{i=1}^{n} \left( \frac{D_i F_i + V_i X_i}{Q_i} \right) + \sum_{i=1}^{n} h P_i \frac{X_i}{Q_i}$$

$$\left( \frac{\sum_{i=1}^{n} X_i}{2} - \sum_{i=1}^{n} dX_i \left( l_i - \arg \min l_i \right) \right)$$

(8)

Therefore, the estimated optimal order quantity ($Q^*$) can be determined from using the partial derivative of $C_{total}$ with respect to $Q$ and then setting the output equal to 0:

$$\frac{\partial C_{total}}{\partial Q} = -\sum_{i=1}^{n} \frac{D F_i A_i}{Q^2} - \sum_{i=1}^{n} \frac{D A_i A_i}{Q^2} + \frac{1}{2} \sum_{i=1}^{n} h P_i X_i = 0$$

(9)

Hence,

$$Q^* = \sqrt{2D \sum_{i=1}^{n} A_i A_i + F_i A_i}$$

$$\frac{h P_i X_i}{(10)}$$

By substituting for $Q^*$ in $C_{total}$, Eq (8), therefore, the objective function of this paper that aims to minimize total cost can be written as equation below:

$$\begin{align*}
\text{Min } Z & = \sum_{i=1}^{n} D X_i \left( P_i + V_i \right) + \frac{D}{2} \sum_{i=1}^{n} \left( A_i + F_i \right) \lambda_i \sum_{i=1}^{n} h P_i X_i - \sum_{i=1}^{n} d h P_i X_i \left( l_i - \arg \min \lambda_i \right) \\
\text{Subject to these constraints,} & \\
Q X_i & \leq c_i, \quad \forall i \\
\sum_{i=1}^{n} Q X_i & \geq Q; \quad \sum_{i=1}^{n} X_i = 1 \\
R - d \left( \arg \min l_i \lambda_i \right) & \geq 0 \\
l_i \lambda_i & \leq T; \quad \forall i \\
Q, X_i, c_i, \lambda_i & \geq 0; \quad Q, c_i \text{ are integer and } \lambda \text{ is binary decision variable}
\end{align*}$$

(11)

(12)

(13)

(14)

(15)

(16)

The first constraint is set to ensure that allocated order quantity to each supplier does not exceed the supplier’s capacity. The second is defined to satisfy the buyer’s demand. The next two constraints are set for no shortage and no late delivery, respectively. The last is a general compulsory condition of optimization that no decision variable is a negative value.

### A NUMERICAL EXAMPLE USING THE MODEL

A numerical example is used to test the model and demonstrate the impact of transportation cost on supplier selection. Three suppliers suffice to aid understanding of the selection of multiple suppliers. Presuming suppliers 1, 2 and 3 quote product prices of $5, $6 and $7, respectively, and each has a limited capacity of 700 units. The annual demand of the buyer is 2,880 units and each unit weighs 5 pounds. Demand rate is 80 units a day. The ordering cost is $15 for each supplier, while the holding rate is set at 20%. The buyer receives the order from supplier 1, 2 and 3 at 6, 5 and 4 days,
respectively. Fixed transportation cost is charged at the same rate of $100 for all suppliers, while variable costs depend on the total weight of product as shown in Table 1. The variable transportation costs are adapted from Tyworth and Ruiz (2000).

### TABLE 1
VARIABLE TRANSPORTATION COSTS FOR SUPPLIER 1, 2 AND 3

<table>
<thead>
<tr>
<th>Supplier 1</th>
<th>Supplier 2</th>
<th>Supplier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lbs)</td>
<td>Cost ($/cwt*)</td>
<td>Weight (lbs)</td>
</tr>
<tr>
<td>1 - 456</td>
<td>42.28</td>
<td>1 - 396</td>
</tr>
<tr>
<td>457 - 830</td>
<td>38.62</td>
<td>397 - 802</td>
</tr>
<tr>
<td>831 - 1,529</td>
<td>32.1</td>
<td>803 - 1,767</td>
</tr>
<tr>
<td>1,530 - 3,508</td>
<td>24.55</td>
<td>1,768 - 3,985</td>
</tr>
</tbody>
</table>

* The cwt is a hundredweight unit (1 cwt = 100 pounds)

### COMPUTATIONAL RESULTS AND DISCUSSIONS

The results are discussed regarding: 1) the examination of the effects of transportation cost; 2) the selection of suppliers and the proportion split of the order among them; and 3) the effects of lead-time on supplier selection.

### EFFECTS OF TRANSPORTATION COST

For each supplier the effects of transportation cost are compared for two models: the general supplier selection model, ignoring transportation cost, hereafter called Gen-SPS, and the proposed model, including transportation cost, hereafter called Proposed-SPS. Infinite capacity is assumed to avoid infeasible solutions. Results for both models are shown in Table 2. For the inclusion of transportation cost are shown in Table 3.

### TABLE 2
RESULTS FOR GEN-SPS AND PROPOSED-SPS FOR EACH SUPPLIER

<table>
<thead>
<tr>
<th>Supplier 1</th>
<th>Supplier 2</th>
<th>Supplier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen-SPS</td>
<td>Proposed-SPS</td>
<td>Gen-SPS</td>
</tr>
<tr>
<td>Q (units)</td>
<td>294</td>
<td>814</td>
</tr>
<tr>
<td>Prc ($)</td>
<td>14,400.00</td>
<td>14,400.00</td>
</tr>
<tr>
<td>Inv ($)</td>
<td>297</td>
<td>467</td>
</tr>
<tr>
<td>Trs ($)</td>
<td>-</td>
<td>2,881.12</td>
</tr>
<tr>
<td>C_total ($)</td>
<td>14,697.00</td>
<td>17,748.12</td>
</tr>
<tr>
<td>Difference</td>
<td>-3,051.12</td>
<td>-6,602.92</td>
</tr>
</tbody>
</table>
TABLE 3
RESULTS FOR GEN-SPS ADDING TRANSPORTATION COST AND PROPOSED-SPS

<table>
<thead>
<tr>
<th>Supplier 1</th>
<th>Supplier 2</th>
<th>Supplier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen-SPS</td>
<td>Proposed-SPS</td>
<td>Gen-SPS</td>
</tr>
<tr>
<td>Trs ($)</td>
<td>5,622.40</td>
<td>2,881.12</td>
</tr>
<tr>
<td>$C_{total}$</td>
<td>20,319.40</td>
<td>17,748.12</td>
</tr>
<tr>
<td>Difference</td>
<td>2,571.28</td>
<td>1,309.72</td>
</tr>
</tbody>
</table>

In Table 2, the optimal order quantity for each supplier using Gen-SPS is smaller than that of Proposed-SPS. A smaller order quantity lowers inventory and total cost. For each supplier, the difference row in Table 2 shows the total cost for Gen-SPS is less that the Proposed-SPS, ranging from 17% to 27%.

When transportation cost is included in total cost for Gen-SPS, the results change as shown in Table 3. The transportation cost is calculated for the optimal order quantity for each supplier. The Proposed-SPS is the same as before. However, adding transportation cost into Gen-SPS swings the difference between the models so that the total costs for Proposed-SPS are now lower than those for Gen-SPS, ranging from 5% to 14%. Small order quantities cause for Gen-SPS requires deliveries to be more frequent, thereby contributing to higher transportation cost.

Comparing total cost for Gen-SPS between Table 2 and Table 3, for suppliers 1, 2 and 3, it increases by 28%, 31% and 30%, respectively. Thus, transportation cost affects supplier selection. In addition, if transportation cost is not considered initially in the model, the buyer has to spend more money on transportation and consequently has a higher total cost. Therefore, transportation cost should be included in the model. Results for applying the model in the selection of multiple suppliers that includes transportation cost are presented in the next section.

RESULTS FOR OPTIMIZING THE SELECTION OF MULTIPLE SUPPLIERS

For the situation where suppliers have limited capacity, Proposed-SPS was applied with the aim to determine which suppliers should be selected and the optimal order quantity that should be split among them. The objective function for this example is formulated as equation below.

\[
\min Z = \sum_{i=1}^{3} 2,880X_i(P_i + V_i) + \sqrt{2 \times 2,880 \sum_{i=1}^{3} (A_i + F_i)X_i} \sum_{i=1}^{3} 0.2P_iX_i \cdot \sum_{i=1}^{3} 80 \times 0.2P_iX_i(l_i - \arg\min_{l_i} \lambda_i) \quad (17)
\]

Subject to, \[ QX_i \leq c_i, \quad i = 1 \text{ to } 3 \quad (18) \]

\[ \sum_{i=1}^{n} QX_i \leq Q; \quad \sum_{i=1}^{3} X_i = 1 \quad (19) \]

\[ R - 80(\arg\min_{l_i} \lambda_i) \geq 0 \quad (20) \]

\[ l_i \lambda_i \leq T; \quad i = 1 \text{ to } 3 \quad (21) \]

\[ Q, X_i, c_i, \lambda_i \geq 0; \quad Q, c_i \text{ are integer and } \lambda \text{ is binary decision variable} \quad (22) \]

This mathematical model is a mixed-integer non-linear programming that is normally difficult to be solved. Care must be taken, as local optima may be found instead of the global optimum. For the example in this paper, the sample space of feasible solutions is not too large to exceed the capacity and solution time, so full search seems to be a reasonable option to guarantee the global optimum solution.

From applied full search to assist with computer programming, the results are found that the optimal order quantity of 1,111 units, with a split to supplier 1 of 700 units and 411 units to supplier 2. This causes purchasing, inventory, transportation and total costs of $15,471.00, $1,201.00, $5,057.45 and $21,729.45, respectively. Moreover, the solution of the inventory and transportation costs were optimized separately are shown in Table 4.
TABLE 4
RESULTS OF INVENTORY (INV) AND TRANSPORTATION (TRS) COSTS OPTIMIZATION

<table>
<thead>
<tr>
<th></th>
<th>Q</th>
<th>Q₁</th>
<th>Q₂</th>
<th>Q₃</th>
<th>Prc</th>
<th>Inv</th>
<th>Trs</th>
<th>C_total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inv optimized</td>
<td>688</td>
<td>0</td>
<td>0</td>
<td>688</td>
<td>20,160</td>
<td>556.6</td>
<td>7,128.32</td>
<td>27,844.92</td>
</tr>
<tr>
<td>Trs optimized</td>
<td>1,111</td>
<td>700</td>
<td>411</td>
<td>0</td>
<td>15,471</td>
<td>1,201.00</td>
<td>5,057.45</td>
<td>21,729.45</td>
</tr>
</tbody>
</table>

Table 4 shows that increasing inventory cost correlates with decreasing transportation cost, and conversely. In addition, it shows the optimal order quantity for Inv optimization of 688 units gives an inventory cost of $556.60, which is 54% less than that for Trs optimization but it causes higher in total cost. In optimizing Trs, purchasing, transportation and total costs are less than for Inv optimization, at $4,689 (30%), $2,071 (41%), and $6,115 (28%), respectively. Therefore, optimizing transportation cost is better than optimizing inventory cost, as savings in transportation cost can be made. However, as both costs conflict, they should be considered simultaneously, so they can be traded off in determining the optimum.

EFFECTS OF VARIED LEAD-TIMES

Lead-time can affect both inventory and transportation costs. The results of varying lead-times are shown in Table 5. As lead-time is varied, only supplier 1 and 2 are selected. This is possibly due to the lead-time not being involved in the calculation of the optimal order quantity, although it has an effect on inventory and total costs. As stated earlier, different lead-times of supplier can allow the buyer to reduce the inventory cost. However, such a reduction can occur when the selected suppliers have different lead-times: the larger the difference in lead-time the greater the reduction.

TABLE 5
RESULTS FOR VARIED LEAD-TIMES

<table>
<thead>
<tr>
<th>Lead-time (lₒ)</th>
<th>Q</th>
<th>Q₁</th>
<th>Q₂</th>
<th>Q₃</th>
<th>Prc</th>
<th>Inv</th>
<th>Trs</th>
<th>C_total</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-4-5</td>
<td>1,110</td>
<td>699</td>
<td>411</td>
<td>0</td>
<td>15,465.60</td>
<td>1,076.64</td>
<td>4,974.80</td>
<td>21,517.04</td>
</tr>
<tr>
<td>6-5-4</td>
<td>1,110</td>
<td>699</td>
<td>411</td>
<td>0</td>
<td>15,465.60</td>
<td>1,188.84</td>
<td>4,974.80</td>
<td>21,629.24</td>
</tr>
<tr>
<td>5-5-4</td>
<td>1,110</td>
<td>699</td>
<td>411</td>
<td>0</td>
<td>15,465.60</td>
<td>1,298.84</td>
<td>4,974.80</td>
<td>21,739.24</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In summary, if transportation cost is ignored, then the decision for supplier selection focuses only on inventory cost, as it can affect supplier selection. In particular, when transportation cost is considered in decisions, the buyer has to balance inventory and transportation costs. As they affect each other, they should be considered simultaneously and not separately and independently. In addition, the total cost was found to be less if both costs are included. Moreover, inventory cost is lower in accordance with larger different lead-time of selected suppliers. However, due to supplier selection is multiobjective problem, taking other objective rather than total cost is a challenging topic for future research.

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