An EOQ Model with Ordering Cost inclusive of a Freight Cost under Condition of Permissible Delay in Payments

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Abstract

As a means of price differentiation, some suppliers may allow credit periods to their customers to increase the demand for their products. Since credit transactions permitted from the supplier may be applied as an effective method to reduce inventory holding costs, it has a positive effect on the customer's order quantity. Also, in many common business transactions, the customer pays the freight cost for the transportation of the order and therefore, the customer's ordering cost consists of a fixed cost and the freight costs that depend on the order quantity. From this point of view, this paper deals with the problem related to decision making of the customer's EOQ (economic order quantity) under condition of permissible delay in payments. It is also assumed that the customer's order cost consists of a fixed cost and the freight costs which constitute a fixed charge for each extra unit load required. We are able to develop a solution algorithm from the properties of an optimal solution, and the validity of the algorithm can be shown through an example problem.

Keywords: Inventory, EOQ, Credit Period, Freight Cost, Quantity Discount

1. Introduction

One of the important extensions of the classical EOQ (Economic Order Quantity) model is the trade credit problem. Credit transactions would play an important role in conducting business for a variety of purposes. In terms of a supplier, credit transaction is being used as an efficient method of price discrimination among their competitors and is also an effective means to increase demand for their products. From a customer's perspective, it is an effective method of ensuring that products of good quality can be supplied and is also an efficient means of reducing inventory holding costs (Fewings[1], Mehta[2] and Shinn[3]). In this regards, many research articles have been conducted on the inventory model under credit transactions. Chung[4], Goyal[5] and Teng et al.[6] analyzes the mathematical model to determine an EOQ on the assumption that the supplier allows a fixed credit period. Kreng and Tan[7] extended the credit model when the supplier permits two levels of credit transactions policy depending

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on the customer’s order size. Also, recognizing that the primary reason for suppliers to allow credit is to stimulate the customer demand for their product, some research papers dealt with the problem of determining the retail price and order size simultaneously. Shinn[3], Chang et al.[8], and Ouyang et al.[9] evaluated the joint pricing and lot sizing problem when the supplier allows a fixed credit period assuming that the customer’s demand rate is a decreasing function of retail price. And they concluded that the availability of the permissible delay in payments from the supplier enables the retailer various pricing options expecting an increase in customer demand.

All the research works mentioned above implicitly assumed a fixed ordering cost without the consideration of any freight cost for the transportation of the quantity ordered. However, in many practical transactions, the customer would pay the freight cost for the order quantity. Aucamp[10], Lee[11] and Lippman[12, 13] evaluated the EOQ model with the ordering cost consisting of a fixed cost and freight cost charged by the volume of the order size. Hwang et al.[14] extended the EOQ model to the case of quantity discounts for both purchasing price and freight cost. Also, Shinn et al.[15] introduced the credit model assuming that the retailer’s ordering cost consist of a fixed cost and freight cost which has a quantity discount.

However, in common business transactions, the quantity purchased may be transported in unit loads, i.e., boxes, pallets, containers, and others. Therefore, there is a basic charge for the first unit load and there is an incremental charge for each more freight unit loads considered as special model by Lee[11]. In this regard, this paper considers the problem of determining the EOQ under circumstances in which the supplier allows a certain delay in payments for the customer’s order quantity. Also, it is assumed that the customer’s ordering cost consists of a fixed cost and a freight cost to be charged depending on each additional unit load required. To determine EOQ for our special model, it may be possible to provide a more efficient solution algorithm than the solution procedure suggested by Shinn et al.[15]. In Section 2, we formulate an appropriate mathematical model to determine the customer’s EOQ. Based on the properties of an optimal solution, a solution algorithm is developed in Section 3. In Section 4, an example problem is provided to demonstrate the validity of the solution algorithm, which is followed by concluding remarks.

2. Development of the Model

The assumptions of this study are essentially same as the EOQ model except for the
The following assumptions and notations are used:

1) The customer’s demand rate is constant.
2) No shortages are allowed.
3) The supplier permits a certain credit period and sales revenue accrued during the credit period is deposited in an interest bearing account with rate $I$. After the credit period has elapsed, the payment is settled and the customer starts paying the inventory investment cost for stock with rate $R (R \geq I)$.
4) The customer pays the shipping cost for the transport of the order quantity.

\[ D = \text{the customer’s annual demand rate.} \]
\[ C = \text{unit purchase cost.} \]
\[ Q = \text{order size.} \]
\[ tc = \text{credit period allowed by the supplier.} \]
\[ H = \text{inventory carrying cost, excluding the capital opportunity cost.} \]
\[ R = \text{capital opportunity cost (as a percentage).} \]
\[ I = \text{earned interest rate (as a percentage).} \]
\[ S(Q) = \text{ordering cost for } Q, (j-1)U < Q \leq jU, j = 1, 2, \ldots, \infty; \ A + F_j. \]
\[ A = \text{fixed ordering cost.} \]
\[ F_j = \text{freight cost for } Q, (j-1)U < Q \leq jU, j = 1, 2, \ldots, \infty; \ P_0 + (j-1)P, \ P_0 \geq P. \]

Namely, as stated by Lee[11], there is a basic charge $P_0$ for the first $U$ freight units and there is an incremental charge $P$ for each $U$ more freight units. In the model with $P_0 = P$, we interpret $U$ as the capacity of each cargo and $P$ as the unit cargo cost. Hence in this case, the freight cost of each order equals $jP$ when the order size satisfies $(j-1)U < Q \leq jU$. Note that the inequality $P_0 > P$ implies that there is some quantity discount in the freight cost for changing the order size from $(j-1)U$ to $jU$. This special case applies in many practical situations, for example, in postal service charges.

The customer’s objective is to minimize the annual total cost, $TC(Q)$ and $TC(Q)$ consists of the following four elements;

1) annual purchasing cost = $CD$.
2) annual ordering cost = $\frac{(A + F_j)D}{Q}$ for $(j-1)U < Q \leq jU$. 
3) annual inventory holding cost = $\frac{HQ}{2}$.

4) annual capital opportunity cost (refer to Goyal[5])

(i) Case 1 ($Dt_c \leq Q$): (see Fig. 1 (a)) As products are sold, the sales revenue is used to earn interest with annual rate $I$ during the credit period $t_c$. And the average number of products in stock earning interest during time $(0,t_c)$ is $\frac{1}{2}Dt_c$ and the interest earned per order becomes $\frac{1}{2}Dt_c \cdot t_cCI$. When the credit is settled, the products still in stock have to be financed with annual rate $R$. Since the average number of products during time $(t_c,Q/D)$ becomes $\frac{1}{2}D(Q/D - t_c)$, the interest payable per order can be expressed as $\frac{1}{2}D(Q/D - t_c) \cdot (Q/D - t_c)CR$. Therefore,

$$\text{annual capital opportunity cost} = \frac{\frac{1}{2}D(Q/D - t_c) \cdot (Q/D - t_c)CR - \frac{1}{2}Dt_c \cdot t_cCI}{Q/D}$$

$$= \frac{C(R-I)D^2t_c^2}{2Q} + \frac{CRIQ}{2} - CRDt_c.$$

(ii) Case 2 ($Dt_c > Q$): (see Fig. 1 (b)) For the case of $Dt_c > Q$, all the sales revenue is used to earn interest with annual rate $I$ during the credit period $t_c$. The average number of products in stock earning interest during time $(0,Q/D)$ and $(Q/D,t_c)$ become $\frac{1}{2}Q$ and $Q$, respectively. Therefore, annual capital opportunity cost = $\frac{\frac{1}{2}Q(Q/D)CI + Q(t_c-Q/D)CI}{Q/D} = \frac{CIQ}{2} - CIDt_c$. 

![Fig. 1] Credit period vs. Replenishment cycle time ($Q/D$)
Then, the annual total cost $TC(Q)$ can be expressed as

$$TC(Q) = \text{Purchasing Cost} + \text{Ordering Cost} + \text{Inventory Holding Cost} + \text{Capital Opportunity Cost}. $$

Depending on the relative size of $Dtc$ to $Q$, $TC(Q)$ can be formulated by the following two expressions;

(1) Case $1(Dtc \leq Q)$

$$TC_{1,j}(Q) = CD + \frac{HQ}{2} + \frac{(A + F_j)D}{Q} + \frac{C(R - I)D^2tc^2}{2Q} + \frac{CRQ}{2} - CRDtc$$

for $(j-1)U < Q \leq jU, j = 1, 2, \ldots, \infty$.  

(2) Case $2(Dtc > Q)$

$$TC_{2,j}(Q) = CD + \frac{HQ}{2} + \frac{(A + F_j)D}{Q} + \frac{C(t)Q}{2} - C(t)Dtc$$

for $(j-1)U < Q \leq jU, j = 1, 2, \ldots, \infty$.  

3. Determination of Optimal Policy

The problem is to find an optimal order quantity $Q^*$ which minimizes $TC(Q)$. For the normal condition $R \geq I$ as stated by Goyal[5], $TC(Q)$ is a convex function of $Q$ for every $i$ and $j$. And so, there exist a unique value $Q_{i,j}$ which minimizes $TC_{i,j}(Q)$ as follows;

$$Q_{i,j} = \sqrt{\frac{2(A_i + F_j)D}{H_i}} \quad \text{where} \quad A_i = A + \frac{1}{2} C(R - I)Dtc^2 \quad \text{and} \quad H_i = H + CR,$$

(3)

$$Q_{2,j} = \sqrt{\frac{2(A + F_j)D}{H_2}} \quad \text{where} \quad H_2 = H + CI.$$  

(4)

Now, from equations (3) and (4), we have a following useful property.

**Property 1.** For any $j$, $Q_{i,j} \geq Dtc$ if and if only $Q_{2,j} \geq Dtc$. If $Q_{i,j} \geq Dtc$, then $TC_{2,j}(Q)$ is decreasing in $Q$ over $Q < Dtc$. If $Q_{2,j} < Dtc$, then $TC_{1,j}(Q)$ is increasing in $Q$ over $Q \geq Dtc$.

**Proof.** From equation (3), $Q_{i,j} \geq Dtc$ can be rewritten as

$$\sqrt{\frac{2(A + F_j)D + C(R - I)D^2tc^2}{H + CR}} \geq Dtc.$$  

(5)

Squaring both side of equation (5) and rearranging,
\[
2(A + F_j)D + C(R - I)D^2te^2 \geq (H + CR)D^2te^2,
\]
\[
\sqrt{\frac{2(A + F_j)D}{H + CT}} \geq Dtc.
\]

Equation (7) implies that \( Q_{2j} \geq Dtc \) and \( Q_{2j} \) is a minimum point of \( TC_{2j}(Q) \), which is a convex function. Thus, \( TC_{2j}(Q) \) is decreasing in \( Q \) over \( Q < Dtc \). Also, from equations (5) and (7), \( Q_{2j} < Dtc \) implies that \( Q_{1j} < Dtc \). Likewise, \( Q_{1j} \) is a minimum point of \( TC_{1j}(Q) \) and so \( TC_{1j}(Q) \) is increasing in \( Q \) over \( Q \geq Dtc \). Q.E.D.

Property 1 states that for \( j \) given, the value \( Q_j^* \) which minimizes \( TC_{i,j}(Q) \), \( i = 1, 2 \), is known to be either \( Q_{i,j} \) or \( Q_{2,j} \) because the annual total cost function is continuous at \( Q = Dtc \). Moreover, if \( Q_{i,j} \geq Dtc \), then \( Q_{i,j} \) becomes \( Q_j^* \). And if \( Q_{i,j} < Dtc \), then \( Q_{2,j} < Dtc \) and \( Q_{2,j} \) becomes \( Q_j^* \).

Also, we can show that \( Q_{i,j} \) and \( TC_{i,j}(Q) \) have the following properties.

Property 2. For \( i \) given, \( Q_{i,j} < Q_{i,j+1}, \ j = 1,2,\cdots,\infty \).

Property 3. For any \( Q \), \( TC_{i,j}(Q) < TC_{i,j+1}(Q), \ i = 1, 2 \) and \( j = 1,2,\cdots,\infty \).

Property 2 indicates that the value of both \( Q_{i,j} \) and \( Q_{2,j} \) are strictly increasing as \( j \) increases. Property 3 implies that both \( TC_{1,j}(Q) \) and \( TC_{2,j}(Q) \) are strictly increasing for any fixed value of \( Q \) as \( j \) increases. Since our problem structure satisfies properties 2 and 3, we are able to adopt the results of Lee[11] in developing the solution algorithm. Now, we present two theorems, Theorem 1 for Case 1 and Theorem 2 for Case 2. Let \( Q_0 \) be the candidate value for the optimal solution, \( Q^* \) which minimizes the annual total cost, \( TC(Q) \).

Theorem 1 (for Case 1). Suppose \((k-1)U < Dtc \leq kU \) for some \( k \). Let \( a \) be the index such that \((a-1)U < Q_{1,0} \leq aU \) where \( Q_{1,0} = \sqrt{\frac{2(A_1 + P_0 - P)}{H_1}} \).

(i) If \( a > k \) and \( Q_{1,a} \leq aU \), then \( Q_0 = (a-1)U, Q_{a,a} \).

(ii) If \( a > k \) and \( Q_{1,a} > aU \), then \( Q_0 = (a-1)U, aU \).

(iii) If \( a \leq k \) and \( Q_{k,k} \leq Dtc \), then \( Q^* \) must less than \( Dtc \).

(iv) If \( a \leq k \) and \( Q_{k,k} \leq kU \), then \( Q_0 = Q_{k,k} \).

(v) If \( a \leq k \) and \( Q_{k,k} \geq kU \), then \( Q_0 = kU \).

Proof. In Case 1\((Q \geq Dtc)\), we will consider three possible case between indexes \( a \) and \( k; \ a > k, \ a = k \) and \( a < k \). By Acaump[10] and Lee[11], we have
\[ TC_{1,j}(Q) > TC_{1,j}(jU) \] for \((j-1)U < Q \leq jU, j < a,\] (8)
\[ TC_{1,j-1}((j-1)U) > TC_{1,j}(jU), j < a,\] (9)
\[ TC_{1,j}(Q) > TC_{1,j-1}((j-1)U) \] for \((j-1)U < Q \leq jU, j > a,\] (10)
\[ TC_{1,j+1}((j+1)U) > TC(jU), j > a.\] (11)

For the first case \((a > k),\) if \(Q_{1,a} \leq aU,\) then we have
\[ TC_{1,a}(Q_{1,a}) \leq TC_{1,a}(Q) \] for \((a-1)U < Q \leq aU\] (12)
\[ \leq TC_{1,a}(aU)\] (13)
Hence, \(Q_o = (a-1)U\) and \(Q_{1,a}.\) Otherwise, \(TC_{1,a}(Q)\) is decreasing function of \(Q\) for \((a-1)U < Q \leq aU.\) Therefore, \(Q_o = (a-1)U\) and \(aU.\)

For the second case \((a = k),\) note that \(Dtc \in [(a-1)U, aU]\) by the definition of \(k.\) So, if \(Q_{1,k} \leq Dtc,\) we have
\[ TC_{1,a}(Dtc) \leq TC_{1,a}(Q) \] for \(Dtc \leq Q \leq aU\] (14)
\[ \leq TC_{1,a}(aU)\] (15)
\[ < TC_{1,j}(Q) \] for \((j-1)U < Q \leq jU, j > a\] (16)
Hence, \(Dtc\) is the minimum point of the annual total cost for \(Q \geq Dtc.\) But we do not need to consider \(Q = Dtc\) as candidate for the optimal solution by Property 1 and the fact that the annual total cost function is continuous at \(Q = Dtc.\) Otherwise, if \(Dtc \leq Q_{1,a} \leq aU,\) then we have
\[ TC_{1,a}(Q_{1,a}) \leq TC_{1,a}(Q) \] for \(Dtc \leq Q \leq aU\] (17)
\[ \leq TC_{1,a}(aU)\] (18)
\[ < TC_{1,j}(Q) \] for \((j-1)U < Q \leq jU, j > a\] (19)
Hence, \(Q_o = Q_{1,a}.\) Otherwise, we have
\[ TC_{1,a}(aU) \leq TC_{1,a}(Q) \] for \(Dtc \leq Q \leq aU.\] (20)
Hence, \(Q_o = aU.\)

Finally, consider the third case, \(a < k.\) By equations (10) and (11), if \(Q_{1,k} \leq Dtc,\) then \(Dtc\) is the minimum point of the annual total cost for \(Q \geq Dtc\) but we do not need to consider \(Q = Dtc\) as candidate for the optimal solution by Property 1. Otherwise, if \(Q_{1,k} \leq kU,\) then \(Q_o = Q_{1,k}.\) Otherwise, \(Q_o = kU.\) Q.E.D.

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Theorem 2 (for Case 2). Suppose \((k-1)U < Dtc \leq kU\) for some \(k\). Let \(b\) be the index such that \((b-1)U < Q_{2,0} \leq bU\) where
\[
Q_{2,0} = \sqrt{\frac{2(A + P_0 - P)}{H_2}}.
\]
(i) If \(b < k\) and \(Q_{2,b} \leq bU\), then \(Q_0 = (b-1)U, Q_{2,b}\).
(ii) If \(b < k\) and \(Q_{2,b} > bU\), then \(Q_0 = (b-1)U, bU\).
(iii) If \(b = k\) and \(Q_{2,b} \leq Dtc\), then \(Q_0 = (b-1)U, Q_{2,b}\).
(iv) If \(b = k\) and \(Q_{2,b} > Dtc\), then \(Q_0 = (b-1)U\).
(v) If \(b > k\), then \(Q_0 = (k-1)U\).

Proof. Now, consider the Case 2\((Q < Dtc)\). Similarly, we will consider three possible case between indexes \(b\) and \(k\); \(b < k\), \(b = k\) and \(b > k\).

For the first case \((b < k)\), if \(Q_{2,b} \leq bU\), then \(Q_0 = (b-1)U\) and \(Q_{2,b}\). Otherwise, \(Q_0 = (b-1)U\) and \(bU\).

For the second case \((b = k)\), note that \(Dtc \in \((b-1)U, bU]\) by the definition of \(k\). So, if \(Q_{2,b} < Dtc\), then \(Q_0 = (b-1)U\) and \(Q_{2,b}\). Otherwise, \(Q_0 = (b-1)U\) and \(Dtc - \epsilon\) where \(\epsilon\) is very small positive number. But we do not need to consider \(Q = Dtc - \epsilon\) as candidate for the optimal solution by Property 1 and the fact that the annual total cost function is continuous at \(Q = Dtc\).

Finally, consider the third case, \(b > k\). First note that \(TC_{2,j}(Q)\) is decreasing for \(Q \in \((j-1)U, jU]\), \(j \leq k\). Therefore,
\[
TC_{2,j}(Q) \geq TC_{2,j}(jU) \quad \text{for} \quad Q \in \((j-1)U, jU]\), \(j \leq k\).
\]

Note also that
\[
TC_{2,j-1}((j-1)U) > TC_{2,j}(jU), \quad j \leq k.
\]

Hence for the case of \(b > k\), \(Q_0 = (k-1)U\) and \(Dtc - \epsilon\). But we do not need to consider \(Q = Dtc - \epsilon\) as candidate for the optimal solution by Property 1 and the fact that the annual total cost function is continuous at \(Q = Dtc\). Therefore, we only need to consider \(Q = (k-1)U\) as candidate for the optimal solution.

Solution algorithm

Step 1. Find index \(k\) such that \((k-1)U < Dtc \leq kU\).
Step 2. Compute $Q_{1,0} = \sqrt{\frac{2(A + P_0 - P)D}{H_1}}$ and find index $a$ such that $(a-1)U < Q_{1,0} \leq aU$.

Step 3. If $a > k$, go to step 4.
Otherwise, go to step 5.

Step 4. If $Q_{1,a} \leq aU$, then compute $TC(Q)$ with equation (1) for $Q = (a-1)U$ and $Q_{1,a}$, and go to step 6.
Otherwise, compute $TC(Q)$ with equation (1) for $Q = (a-1)U$ and $aU$, and go to step 6.

Step 5. If $Q_{1,k} \leq Dtc$, then go to step 6.
Otherwise, if $Q_{1,k} \leq kU$, then compute $TC(Q)$ with equation (1) for $Q = Q_{1,k}$ and go to step 6.
Otherwise, compute $TC(Q)$ with equation (1) for $Q = kU$ and go to step 6.

Step 6. Compute $Q_{2,0} = \sqrt{\frac{2(A + P_0 - P)D}{H_2}}$ and find index $b$ such that $(b-1)U < Q_{2,0} \leq bU$.

Step 7. If $b < k$, then go to step 8.
Otherwise, if $b = k$, then go to step 9.
Otherwise, go to step 10.

Step 8. If $Q_{2,b} \leq bU$, then compute $TC(Q)$ with equation (2) for $Q = (b-1)U$ and $Q_{2,b}$, and go to step 11.
Otherwise, compute $TC(Q)$ with equation (2) for $Q = (b-1)U$ and $bU$, and go to step 11.

Step 9. If $Q_{2,k} \leq Dtc$, then compute $TC(Q)$ with equation (2) for $Q = (b-1)U$ and $Q_{2,k}$, and go to step 11.
Otherwise, compute $TC(Q)$ with equation (2) for $Q = (b-1)U$ and go to step 11.

Step 10. Compute $TC(Q)$ with equation (2) for $Q = (k-1)U$ and go to step 11.

Step 11. Select the one that yields the minimum cost as $Q^*$ and stop.

4. Numerical Example

The traditional credit model analyzes solely the case of fixed ordering cost. However, in many practical problems, the customer pays the freight cost for the transportation of the order and the order may be transported in unit loads, i.e., boxes, pallets, containers, and others. From this point of view, we considered the situation that the customer’s ordering cost consists of a fixed cost and a freight cost to be charged depending on the order size. The following example will be used to illustrate the solution algorithm.

Let $D = 3,200$ units, $A = $50, $C = $3, $H = 0.3,$ $R = 0.15 (=15\%),$ $I = 0.1 (=10\%),$ $tc = 0.3$, $
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\[ U = 300, \quad P_0 = 15, \quad P = 10. \] To solve the problem, a computer program written QBASIC was developed to find the optimal solution as follows;

Step 1. \( D t c = 960 \in [3 \times 300, 4 \times 300] \). So, \( k = 4 \).
Step 2. \( Q_{4,0} = 808 \in [2 \times 300, 3 \times 300] \). So, \( a = 3 \).
Step 3. Because \( a(=3) < k(=4) \), go to step 5.
Step 5. \( Q_{4,4} = 997 \). Because \( D t c (= 960) < Q_{4,4} \leq kU (= 1,200) \), compute the annual total cost with equation (1) at \( Q_0 = Q_{4,4} \) and go to step 6.
Step 6. \( Q_{2,0} = 766 \in [2 \times 300, 3 \times 300] \). So, \( b = 3 \).
Step 7. Because \( b(=3) < k(=4) \), go to step 8.
Step 8. \( Q_{3,3} = 952 \). Because \( bU (= 900) \), compute the annual total cost with equation (2) at \( Q_0 = (b-1)U (= 600) \) and \( bU (= 900) \). Go to step 11.
Step 11. Since \( TC_{1,4}(Q_{4,4}) = 9916.12 \), \( TC_{2,2}(2U) = 9892.00 \) and \( TC_{2,3}(3U) = 9884.22 \), an optimal order quantity, \( Q^* \) becomes \( 3U (= 900) \) with its minimum annual total cost, $9884.22.

To determine the customer’s EOQ, the availability of credit period from the supplier has a positive effect on the order quantity. Following the solution algorithm, we only need to consider \( Q = Q_{4,4}, 2U, 3U \) for finding the customer’s optimal order quantity. After comparing the annual total cost values, the customer’s optimal order quantity \( Q^* \) becomes \( 3U (= 900) \) with its minimum annual total cost, $9884.22.

5. Conclusions

We have analyzed the EOQ (Economic Order Quantity) problem in which the customer’s ordering cost consists of a fixed cost and a freight cost when the supplier provides a certain fixed credit period for settling the amount the customer owes to him. Frequently, the freight cost is not linearly proportional to the order size. In many practical situations, the order may be transported in unit loads, i.e., boxes, pallets, containers, and others and therefore, the freight cost constitutes a fixed charge for each extra carload required. From this point of view, the model considered in this paper seems more realistic.

For the system presented, a mathematical model was developed. After formulating the mathematical model, we found the characteristics of the annual total cost function and developed the solution algorithm which is more efficient than the solution algorithm presented.
by Shinn et al.[15]. To illustrate the validity of the solution algorithm, an example problem was chosen and solved.

References


