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Economic order quantity model for items with imperfect quality and multiple suppliers

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Abstract

Economic order/production quantity (EOQ/EPQ) models for imperfect items have received great attention in the last decade. The main common feature of these models is the incorporation of the imperfect items into the problem. While in real-world problems, buyers usually work with multiple suppliers, the focus of the existing literature has been on a single-supplier variant of the problem. In this study, we formulate an EOQ model for items with imperfect quality when considering multiple suppliers, which is a particular type of supplier selection and EOQ models. The initial formulated problem is a mixed integer nonlinear programming that aims to maximize the total annual profit of the buyer such that customer demand is completely met and suppliers' capacity constraints are satisfied. Since proposed model is nonlinear, first by using the unique property of model, it is converted to mixed integer linear programming then solved by GAMS/CPLEX software to obtain optimal solution. We then use a numerical example to illustrate the problem, and conduct a sensitivity analysis to study the sensitivity of the objective function and the decision variables to the imperfect rate of the items supplied by the selected suppliers.

Keywords: Order splitting, EOQ/EPQ, imperfect quality, supplier selection, linearization

1- Introduction

Supply chain management (SCM), as a paradigm shift has led to a new generation of problem solving approaches in management studies. SCM calls for a "systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company" (Mentzer et al., 2001). This implies that it is no longer efficient to model business problems individually. Reviewing the literature reveals that there has been an increasing trend in formulating integrative problems. Some of the most interesting examples are "supplier integration into new product development" (Petersen et al., 2005), "inventory management and information sharing" (Cachon and Fisher, 2000), "marketing/logistic cross-functional collaboration" (Ellinger, 2000). We contribute to this growing stream by developing an integrative model for inventory management and supplier selection. While for decades these two problems have been handled individually, some researchers have attempted to propose models integrating these two problems (see for example Tempelmeier , 2002, Basnet and Leung, 2005; Aissaoui et al., 2007, Rezaei and Davoodi, 2006, 2008, 2011, 2012, Ustun, 2008, Guo and Li, 2014, Saputro et al., 2021, Ventura et al., 2021). Supplier selection problem can be considered as a problem in which a buyer evaluates a set of potential suppliers to select a predetermined number of the best suppliers. Multiple criteria are involved in this evaluation and selection, which is why several multi-criteria and multi-objective decision-making methods have been applied to formulate and solve this problem.

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To see these applications we refer to the review papers De Boer et al., (2001), Ho et al., (2010), Chai et al., (2012), Chai and Ngai (2020). It is obvious that the selected suppliers should supply the material/products demanded by the buyer.

Inventory management is responsible for handling material/products. It then becomes clear that supplier selection and inventory management are two connected problems which should be handled together. In other words, solving these two problems separately brings us to a near-optimal of the integrated problem. Inventory management, like supplier selection, is a very well established field.

The first inventory management model called the Economic Order Quantity (EOQ) was proposed by Harris (1915) a century ago. The goal is to find the optimal order quantity such that the total costs of the problem (holding costs, and ordering costs) are minimized and the total demand is met. Since then several interesting extensions of the EOQ model have been proposed in literature. Some of the most promising examples are "EOQ for perishable products" (Nahmias, 1982), "EOQ for reusable products (Koh et al., 2002), "EOQ for growing items" (Rezaei, 2014) and "EOQ for imperfect items" (Salameh and Jaber, 2000). In this paper, we formulate and solve the integrative problem of supplier selection and EOQ for imperfect items. In traditional EOQ models, it is implicitly assumed that the items received are of perfect quality. However, it may not always be the case. Due to imperfect production process, natural calamities, damage or breakage in transit, or for many other reasons, the lot received may contain some items with imperfect quality (Chang, 2004).

Items of imperfect quality, not necessarily defective, could be used in another production/inventory situation (Salameh and Jaber, 2000). Imperfect items, as a consequence of considering imperfect quality of the production process were initially incorporated by Porteus (1986), Rosenblatt and Lee (1986) and Lee and Rosenblatt (1987). Besides imperfect quality assumption in production process, many other reasons such as damages and breakages during inbound and outbound transportation may also result in defective items. Salameh and Jaber (2000), are the first researchers who developed an EOQ model for imperfect items. They considered a situation where each received lot contains a percentage of defective items with a known probability density function. A 100% inspection is conducted, and at the end of the inspection process imperfect items are sold in a single batch at a discounted price. The original work of Salameh and Jaber (2000) has been extended by other researchers (see for example Cárdenas-Barrón, 2000, Goyal and Cárdenas-Barrón, 2002, Chang, 2004, Rezaei, 2005, 2016, Papachristos and Konstantaras, 2006, Maddah and Jaber, 2008, Hsu and Yu, 2009, Khan et al., 2010, Rezaei and Salimi, 2012, Konstantaras et al., 2012, Hsu and Hsu, 2013, Jaber et al., 2014, Kazemi et al., 2015, 2018, Nobil et al.,2020, Asadkhani et al., 2022).

Integrating the two problems of supplier selection and inventory models provides the buyer with an optimal solution which shows "what quantities to order with which suppliers". While most work on EOQ with imperfect items have considered a single supplier (see the review paper Khan et al., 2011), this paper aims to formulate and solve a joint model for EOQ with imperfect items and multiple suppliers to consider the effect of imperfect items in received orders from suppliers on buyer's inventory level. Thus developing an integrated approach to determine the optimal ordering policy for a single imperfect item multi supplier system is the major contribution of our study. The remainder of the paper is organized as follows. Section 2 presents the mathematical model, and solution approach of the problem. In Section 3 numerical examples are presented to show the behavior of the model. Finally, conclusions and directions of future research are discussed in Section 4.

2- Problem definition and formulation

Consider a procurement situation in which a single item can be purchased from a set of n potential suppliers with limited capacity. The buyer would like to select the best suppliers among the set and assign the order quantities to them, such that the demand of item is fully met, the capacity constraint are satisfied and total profit is maximized. We assume that the received lots from the selected suppliers contain items with imperfect quality. A 100% inspection is conducted to separate imperfect items which are sold at a reduced price at the end of the inspection period. The buyer would like to selected the best suppliers among the set of potential suppliers and assign the order quantities to them such that the demand of items is fully met, the capacity constraints are satisfied and the total profit is maximized.

2-1- Notations and assumptions

The following notations and assumptions are used to develop the proposed model.

Notations:

i: index of suppliers
n: number of suppliers
D: annual demand rate
r: inventory holding cost rate
h_i: inventory holding cost per unit per year from ith supplier ($h_i=rc_i$)
x: annual inspection rate
d: unit inspection cost
s: unit selling price of perfect quality items
v: unit selling price of imperfect quality items($v < c_i$)
F_i: annual supplier management cost incurred when selecting ith supplier (any cost associated with keeping a long term relationship with a supplier)
A_i: ordering cost of ith supplier
c_i: unit purchasing price of ith supplier
p_i: imperfect rate of ith supplier
ca_i: annual capacity of ith supplier
D_i: annual ordering quantity from ith supplier
Q_i: the quantity of a single order from ith supplier
y_i: binary variable; if the ith supplier is selected , $y_i=1$, otherwise it is 0.

Assumptions:

1. Buyer orders only when inventory is zero
2. At each order epoch only one order is placed with one supplier
3. All orders to supplier i, Q_i, are of the same size
4. Each received lot from ith supplier contains a p_i (a known fraction) of imperfect items
5. To avoid shortage, the quantity of perfect items in each lot of ith supplier should be greater than or equal to the demand during the inspection time t_i , that is: $Dt_i \leq Q_i(1-p_i)$ where t_i is equal to (Q_i/x). As a result, (p_i) must not exceed $(1-D/x)$, i.e: $p_i \leq 1-D/x$
6. Imperfect items of each lot is treated as a single batch and sold at discounted price immediately when the inspection process ends
7. As soon as receiving each lot, a 100% inspection process is carried out at a fixed cost per unit and at a rate much higher than demand (Notice that the inspection process and demand proceeds simultaneously).

Figure 1 illustrates buyer’s inventory level for an instance of three selected suppliers based on the assumptions of the problem.

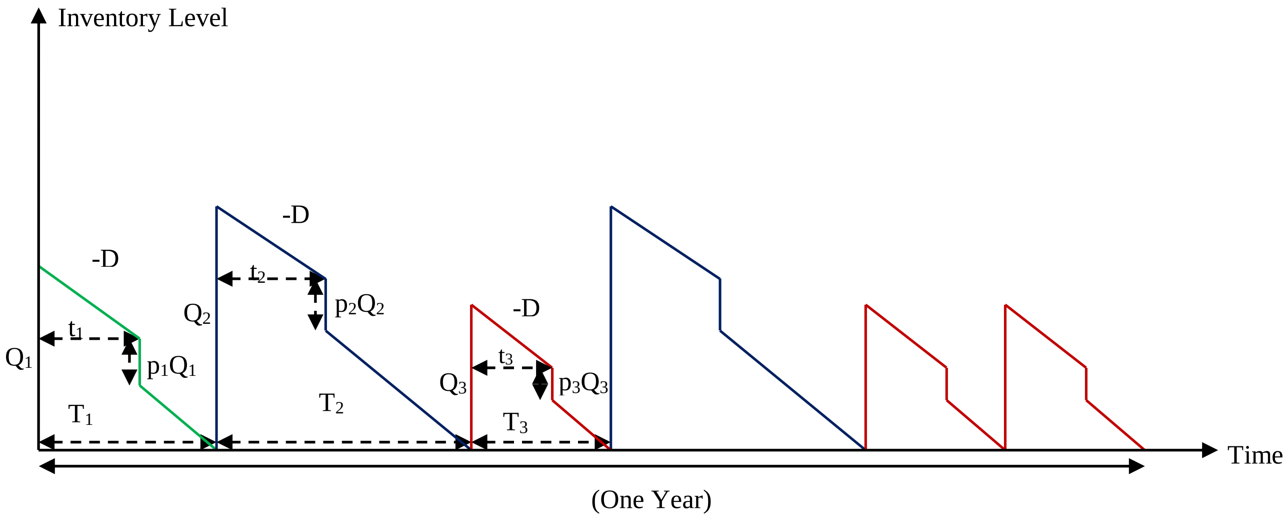

Fig 1. Inventory level of buyer for three selected supplier

2-2- Objective function

The objective function of the proposed model is the total annual profit (*TAP*) that equals the total annual revenue (*TAR*) less the total annual cost (*TAC*).

Total annual revenue is the sum of total sales volume of perfect quality items and imperfect quality items. Total annual cost is the sum of annual ordering cost *(AOC*), annual purchasing cost *(APC)*, annual inspection cost *(AIC)*, annual holding cost *(AHC)* and annual suppliers' management cost *(ASMC)*.

Therefore the objective function of the model which is a non-linear function is given as follows.

$$TAP = TAR - TAC = TAR - (AOC + APC + AIC + AHC + ASMC)$$
$$= \sum_{i=1}^{n}(s(1-p_i)D_i + vp_iD_i) - \sum_{i=1}^{n}[\frac{A_iD_i}{Q_i} + c_iD_i + dD_i + h_i(Q_iD_i \times (\frac{(1-p_i)^2}{2D} + \frac{p_i}{x}))] - \sum_{i=1}^{n}F_iy_i \quad (1)$$

2-3- Constraints

Two types of constraints, demand constraint and capacity constraint, are associated with the problem. The demand constraint ensures that buyer's demand is satisfy by the total order received from selected suppliers. The capacity constraint ensures that the annual order assigned to each selected supplier is not larger than his/her capacity. In the following these constraints are formulated.

$$\sum_{i=1}^{n} D_i(1-p_i) = D \quad (2)$$

$$D_i \le ca_i y_i \qquad \forall i = 1,\ldots,n \quad (3)$$

2-4- Final model

It can be shown that the formulated objective function is concave with respect to Qi. Thus by setting the first derivatives of objective function with respect to Qi to zero, we get optimum value of Qi to be:

$$\frac{\partial TAP}{\partial Q_i} = 0 \Rightarrow Q_i^* = \sqrt{\frac{A_i}{h_i\left(\frac{(1-p_i)^2}{2D} + \frac{p_i}{x}\right)}} \quad (4)$$

Notice that Q_i^* is not a function of D_i. So according to this unique property, we can obtain the following simplified expression for objective function by substituting Q_i^* in *TAP*.

$$TAP = \sum_{i=1}^{n} D_i[(s(1-p_i) + vp_i) - 2\sqrt{A_ih_i\left(\frac{(1-p_i)^2}{2D} + \frac{p_i}{x}\right)} - (c_i + d)] - \sum_{i=1}^{n} F_i y_i \quad (5)$$

Observe that the above simplified objective function does not include any nonlinear term. So, the final mixed integer linear programming is as follows:

$$Max \quad TAP = \sum_{i=1}^{n} D_i[(s(1-p_i)+vp_i) - 2\sqrt{A_i h_i\left(\frac{(1-p_i)^2}{2D}+\frac{p_i}{x}\right)} - (c_i+d)] - \sum_{i=1}^{n} F_i y_i \tag{6}$$

$s.t:$

$$\sum_{i=1}^{n} D_i(1-p_i) = D \tag{7}$$

$$D_i \le ca_i y_i \quad \forall i = 1,\dots,n \tag{8}$$

$$y_i \in \{0,1\} \quad \forall i = 1,\dots,n \tag{9}$$

$$D_i \ge 0 \quad \forall i = 1,\dots,n \tag{10}$$

3- Numerical example and sensitivity analysis

Assume that the purchasing manager of a company would like to buy one product from a sub-set of 8 potential suppliers with information as given in table 1. It is assumed that the received items are not of perfect quality. The necessary time for inspection of one unit and relevant cost that are calculated by quality control department are 30 minutes and 1.5$, respectively. Assuming that the inspection process runs 8 hours per day, for 365 days a year, the annual inspection rate x would be 5840 units/year. In addition, D = 1000 units/year, r = 0.1 unit/year, s = $50/unit and v = $10/unit.

Table 1. Suppliers' information

Supplier	ca_i	p_i	c_i	A_i	F_i
1	173	0.03	30	40	390
2	150	0.02	32	25	220
3	270	0.11	26	19	180
4	165	0.07	24	28	260
5	180	0.05	28	35	157
6	205	0.09	25	23	294
7	300	0.03	29	29	327
8	244	0.06	26	33	432

Considering the aforementioned data, a mixed integer linear programming is formulated. To solve the formulated problem we use a GAMS/CPLEX software. Notice that the optimal value of Qi for each selected supplier must be then obtained from equation (6). Table 2 shows the optimal solution.

Table 2. Optimal solution

Supplier	y_i	D_i	Q_i^*
1	0	0	-
2	0	0	-
3	1	270	132.7168
4	1	165	162.0200
5	0	0	-
6	1	205	146.3632
7	1	196.227	145.0056
8	1	244	167.5581
Optimal value of objective function		19175.9868	

3-1- An important property of the optimal solution

In line with what has been found by Rosenblatt et al. (1998) the optimal solution of the problem proposed in our paper is featured by a special property as follows:

There exists an optimal solution to the proposed model where there is at most one supplier who gets the annual order less than its capacity. Any other suppliers either get a full-capacity order or get a zero order (if supplier is not selected). For instance, in our case, only supplier 7 gets an annual order less than his capacity (D7=196.227) (see table 2). Suppliers 3, 4, 6 and 8 get a full capacity order and the other suppliers get a zero order because they are not selected by the buyer.

3-2- Sensitivity analysis

In this section we perform a sensitivity analysis with respect to imperfect rate of each supplier (pi) to investigate its effect on objective function and decision variables.

As the problem is a multiple-supplier problem we can investigate the sensitivity of the objective function and the decision variables to the imperfect rate of individual selected suppliers. For instance, figure 2 shows the sensitivity of objective function to p6 (the imperfect rate of supplier 6), and table 3 shows the sensitivity of Di to change in p6.

According to figure 2, by increasing the value of p6 to 0.17, the objective function reduces, but any increase after this point has no effect on the value of objective function. This is because at this point the set of selected suppliers changes, which means that the supplier 5 with an annual purchase volume of 185 units is replaced with supplier 6. Thus it becomes clear that no change is made in the objective function.

Also according to table 3, it can be observed that when p6 increases to 0.16, the amount of D7 enhances because the number of good quality items purchased from supplier 6 reduces and thus to satisfy the annual demand, shortage resulting from supplier 6 must be compensated by more purchase from other supplier, and because among the set of selected suppliers only the supplier 7 has free capacity, this shortage is compensated by more purchase from that supplier.

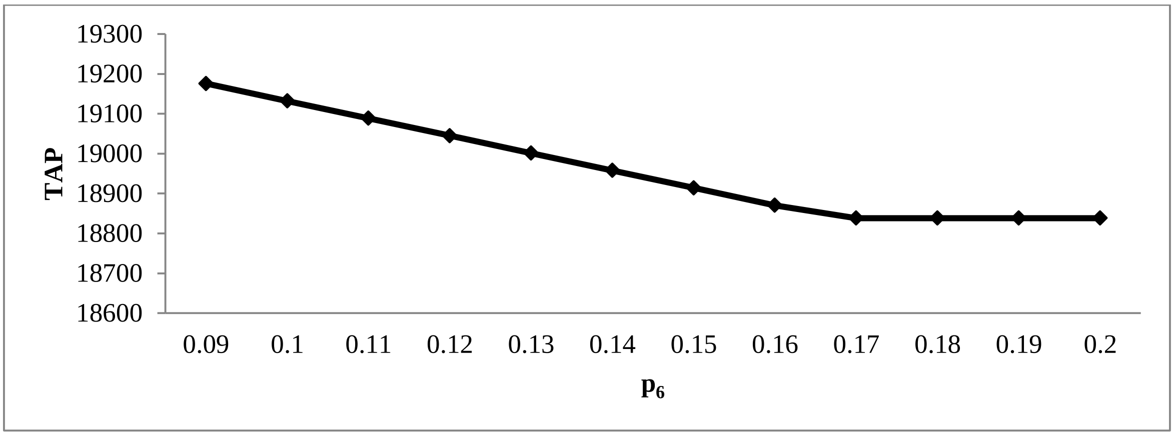

Fig 2. Changing trend of total annual profit with respect to imperfect rate of sixth suppliers

Table 3. Changing trend of D_i with respect to imperfect rate of sixth suppliers

D_i \ p_6	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
D_1	0	0	0	0	0	0	0	0	0	0	0	0
D_2	0	0	0	0	0	0	0	0	0	0	0	0
D_3	270	270	270	270	270	270	270	270	270	270	270	270
D_4	165	165	165	165	165	165	165	165	165	165	165	165
D_5	0	0	0	0	0	0	0	0	185	185	185	185
D_6	205	205	205	205	205	205	205	205	0	0	0	0
D_7	196.2	198.3	200.4	202.5	204.6	206.7	208.9	211.0	212.2	212.2	212.2	212.2
D_8	244	244	244	244	244	244	244	244	244	244	244	244

A similar sensitivity analysis can be conducted for the other suppliers.

4- Conclusions

In current research, we have studied the problem of supplier selection and order splitting when received orders from selected supplier contain some imperfect quality items. The inventory management of procured items and ordering policy is considered based on EOQ concept. We formulate this problem as a mixed integer nonlinear programming that maximizes the total annual profit of buyer, while properly determining the annual purchase volume from selected suppliers as well as quantity of a single order for each of them. Then, by using the unique property of the proposed model, it is converted to a mixed integer linear programming which can then by simply solved using a GAMS/CPLEX software to obtain the optimal solution. A numerical example was used to demonstrate the proposed model. We also studied the sensitivity of the objective function and decision variables of the model to the core parameter of the model which the imperfect rate of the suppliers. The results indicate that the total annual profit can be decreased by increasing the imperfect rate of each selected suppliers.

We think that this particular study can be extended in several directions. Firstly, the proposed model can be extended to a centralized supply chain with considering benefits for both suppliers and buyer. Some other interesting future research would be incorporating some other features of the problem for instance the case multi-item problem, or back-ordering policy.

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