A joint economic lot-sizing problem with fuzzy demand, defective items and environmental impacts

W A Jauhari$^1$ and P W Laksono$^2$

$^1$,$^2$Department of Industrial Engineering, Sebelas Maret University, Surakarta, Indonesia

E-mail: wachid_aj@yahoo.com

Abstract. In this paper, a joint economic lot-sizing problem consisting of a vendor and a buyer was proposed. A buyer ordered products from a vendor to fulfill end customer’s demand. A production rate was assumed to be adjustable to control the output of vendor’s production. A continuous review policy was adopted by the buyer to manage his inventory level. In addition, an average annual demand was considered to be fuzzy rather than constant. The proposed model contributed to the current inventory literature by allowing the inclusion of fuzzy annual demand, imperfect production emission cost, and adjustable production rate. The proposed model also considered carbon emission cost which was resulted from the transportation activity. A mathematical model was developed for obtaining the optimal ordering quantity, safety factor and the number of deliveries so the joint total cost was minimized. Furthermore, an iterative procedure was suggested to determine the optimal solutions.

Keywords: Inventory; continuous review; fuzzy demand; adjustable production rate; joint total cost.

1. Introduction
In the last few decades, new technologies have grown exponentially and are changing the world trade. The globalization of market and increased competition will definitely shape the future of supply chain logistics. Integrating vendor–buyer inventory system is critical to lower the joint total cost of supply chain and gain competitive advantages [1]. In inventory literature, the problem concerning with production and inventory decisions is known as joint economic lot-sizing problem (JELP). Goyal [2] was the first researcher who introduced JELP involving a vendor and a buyer under deterministic demand. Banerjee [3] relaxed the assumption of infinite production rate used by Goyal and proposed that the vendor has a finite production. Furthermore, the model of Goyal [2] was then extended into various cases, i.e. discount [4], defective items [5], inspection errors [6] and learning [7].

Previous research on JELP focused on the production shipment schedule in terms of the number and quantity of batches delivered from vendor to buyer. However, most of these models assumed that the demand is deterministic rather than stochastic. In reality, the demand changes over time assuming it to be deterministic was too restrictive assumption. Ben-Daya and Hariga [8] proposed a JELP consisting of a vendor and a buyer with stochastic demand and variable lead time. Hsiao [9] proposed...
two kinds of the reorder point in a continuous review JELP under stochastic demand. Glock [10] analyzed the lead time reduction strategies where the transportation time can be reduced using a crashing cost. Jauhari and Winingsih [11] developed JELP involving of a vendor and a buyer with freight and quantity discount, and considered a quantity discount.

In most of the earlier literature dealing with stochastic JELP, researchers have assumed that the production process was 100% defect-free. In reality, the production process is imperfect due to an unreliable process. Lin [12] developed periodic review integrated vendor-buyer model with imperfect production and backorder price discount. Jauhari et al. [13] then developed the model of Lin [12] by proposing adjustable production rate and variable lead time. Furthermore, Lin and Lin [14] studied the impact of vendor’s recovery process and the investment in reducing ordering cost in a JELP.

One major drawback of published stochastic JELP was that most of the authors assumed that the annual demand was treated as a constant parameter rather than fuzzy. In reality, it is usually difficult for managers to set demand as crisp values due to lack of data, e.g., new product introduction and single period setting. Thus, fuzzy set theory is reasonable to be used to address inventory problems. In addition, in most of published stochastic JELP, researchers have neglected environmental issues, i.e., carbon emission and energy, in developing the inventory models. Environmental issues are becoming more of a concern to supply chain stakeholders, and investigating them in the modeling and design of supply chains is necessary [15].

Based on the above description, a stochastic JELP has been discussed in the past, but none has considered the inclusion of fuzzy demand, carbon emission cost and imperfect production. Therefore, we propose a JELP consisting of a vendor and a buyer under situation in which the annual demand is treated as fuzzy, the production rate is adjustable and the production process is imperfect. In addition, the carbon emission resulted from transportation activity is also considered in the model.

2. Problem statement
Let us consider a supply system consisting of a vendor and a buyer. The buyer faces demand from end customers which is assumed to follow normal distribution with demand rate \( D \) and standard deviation \( \sigma \). A continuous review policy is adopted by the buyer to manage his inventory level. The buyer orders \( nQ \) units to the vendor to satisfy the end customer’s demand. An ordering cost \( A \) is charged to the buyer for each order. The demand that cannot be satisfied by the buyer is assumed to be fully backordered. The vendor produces a batch of product \( nQ \) with a finite production rate \( P (P > D) \). The vendor incurs a setup cost \( K \) for each production run. The vendor then delivers a batch of product over \( n \) times in each production run. The demand during lead time of the first shipment is assumed to follow normal distribution with mean \( DL(Q) \) and standard deviation \( \sigma \sqrt{L(Q)} \).

A production process is not 100% perfect, so it will produce a certain number of defective products with a known probability. Consequently, the lot received by the buyer may contain defective products. Thus, the buyer will inspect the incoming lot to categorize the quality of the product. A screening cost \( s \) is charged to the buyer for each unit product. After finishing the screening process, the defective items found by the inspector will be returned to the vendor. For each item returned by the buyer, the vendor will incur warranty cost \( w \). In addition, the production rate is adjustable between \( P_{\text{min}} \) and \( P_{\text{max}} \).

The objective function of the model is to minimize the joint total cost for the supply chain system and determine the decision variables, which are the size of equal shipments from the vendor to the buyer \((Q)\), safety factor of first shipment \((k_i)\) and the number of deliveries \((n)\). Whereas the parameters used in the proposed model are denoted by these following notations:

\[
\begin{align*}
D & : \text{demand rate in units per unit time;} \\
\sigma & : \text{standard deviation of demand per unit time;} \\
A & : \text{ordering cost per order;} \\
F & : \text{transportation cost per shipment;} \\
h_b & : \text{holding cost per unit per unit time for} \\
S_b & : \text{fixed carbon emission cost for buyer;} \\
S_v & : \text{fixed carbon emission cost for vendor;} \\
z_b & : \text{buyer’s variable carbon emission cost;} \\
z_v & : \text{vendor’s variable carbon emission cost;} \\
a_f & : \text{fixed production cost;}
\end{align*}
\]
buyer;  
\( h_b \) : holding cost per unit per unit time for vendor;  
\( a_2 \) : variable production cost;  
\( \pi \) : backorder cost per unit backordered;  
\( P \) : production rate in units per unit time;  
\( Y \) : defect rate;  
\( K \) : setup cost;  
\( w \) : warranty cost per unit item;  
\( L(Q) \) : lead time as a function of shipment size;  
\( s \) : screening cost per unit item;  
\( T_w \) : setup and transportation time;  
\( x \) : screening rate;  
\( T_s \) : transportation time;  

3. Model development  
Suppose that the demand during lead time of the first shipment is normally distributed with mean \( DL(Q) \) and standard deviation \( \sigma \sqrt{L(Q)} \). As we assumed in previous section that the incoming lot contains some defective items with a percentage \( Y \) and has the probability density function \( f(y) \). Then, the average inventory level of the buyer is can be formulated as \( E \left( \frac{y}{1-Y} \right) \frac{QD}{x} + \frac{1-Y(y)}{2} + k_1 \sigma \sqrt{Q/p + T_w} \) and the safety stock is \( k_1 \sigma \sqrt{Q/p + T_w} \). The expected holding cost for the buyer per year is given by  
\[
h_b \left( E \left( \frac{y}{1-Y} \right) \frac{QD}{x} + \frac{1-Y(y)}{2} + k_1 \sigma \sqrt{Q/p + T_w} \right)
\]
(1)  
The expected of the number of backorders per year can be calculated by considering the number of cycles per year \( E \left( \frac{y}{1-Y} \right) \frac{D \alpha}{nQ} \) number of backorder for first shipment \( \sqrt{Q/p + T_w} \psi(k_1) \) and the number of backorder of next shipments \( (n-1)\sqrt{T_s} \psi(k_2) \), which is  
\[
E \left( \frac{1}{1-Y} \right) \frac{D \alpha}{nQ} \left( \sqrt{Q/p + T_w} \psi(k_1) + (n-1)\sqrt{T_s} \psi(k_2) \right)
\]
(2)  
Here, we also consider the carbon emission cost resulted from transportation activity. The expected fixed carbon emission cost for buyer per year is \( E \left( \frac{1}{1-Y} \right) \frac{DS_b}{Q} \) and the expected variable carbon emission cost for buyer is \( E \left( \frac{1}{1-Y} \right) D_b D \). Thus, the expected carbon emission cost incurred by the buyer is given by  
\[E_b = E \left( \frac{1}{1-Y} \right) \frac{DS_b}{Q} + E \left( \frac{1}{1-Y} \right) D_b D\]
(3)  
Thus, the expected total cost for the buyer composing of ordering cost, transportation cost, inspection cost, carbon emission cost, holding cost and backorder cost, is given by  
\[
ETC_b = E \left( \frac{1}{1-Y} \right) \frac{D}{nQ} (A + nF) + E \left( \frac{1}{1-Y} \right) sD + E \left( \frac{1}{1-Y} \right) \frac{DS_b}{Q} + E \left( \frac{1}{1-Y} \right) D_b D
\]
(4)  
The expected vendor’s inventory level can be calculated by subtracting the accumulated buyer’s consumption from accumulated vendor’s production. The expected vendor’s holding cost per year is expressed by  
\[h_v \left( \frac{n}{2} \right) \left[ 1 - E \left( \frac{1}{1-Y} \right) \frac{D}{P} \right] - 1 + E \left( \frac{1}{1-Y} \right) \frac{2D}{P} \]
(5)  
The expected carbon emission cost resulted from delivering defective items from buyer to vendor is given by  
\[E_v = E \left( \frac{1}{1-Y} \right) \frac{D_v}{Q} + E \left( \frac{1}{1-Y} \right) D_v D\]
(6)
The expected vendor’s cost composing of setup cost, warranty cost, carbon emission cost, holding cost and production cost, is given by the following expression:

\[
ETC_v = E \left( \frac{1}{1-Y} \right) \frac{DK}{Q} + E \left( \frac{Y}{1-Y} \right) wD + E \left( \frac{Y}{1-Y} \right) z_v D + E \left( \frac{1}{1-Y} \right) DS_v
\]

\[
h_v \left( \frac{Q}{2} \right) n \left[ 1 - E \left( \frac{1}{1-Y} \right) \right] - 1 + E \left( \frac{1}{1-Y} \right) \frac{2nb}{p} + E \left( \frac{1}{1-Y} \right) \left( \frac{a_1}{p} + a_2 p \right) \right] D
\]

(7)

By using equation \( M = E \left( \frac{1}{1-Y} \right) \) and \( D \) is fuzzified to be \( \tilde{D} \), the expected total cost for supply chain is given by

\[
E[TTC] = \frac{M \tilde{D}}{nQ} (A + nF) + MS \tilde{D} + \frac{M \tilde{D} S_b}{Q} + Mz_v \tilde{D} - z_v \tilde{D}
\]

\[
+ h_b \left( \frac{MQ \tilde{D}}{x} - \frac{Q \tilde{D}}{x} + \frac{[1 - E(Y)]Q}{2} + k_1 \sigma \sqrt{Q/p + T_w} \right)
\]

\[
+ \left( \frac{M \pi \tilde{D} \sigma}{nQ} \right) \left( \sqrt{Q/p + T_w} \Psi (k_1) + (n - 1) \sqrt{T_w} \Psi (k_2) \right) + \frac{M \tilde{D} \Psi}{Q} + M \tilde{D} - \tilde{D} - z_v \tilde{D}
\]

\[
+ h_v \frac{Q}{2} (n \left[ 1 - \frac{M \tilde{D} \Psi}{p} \right] - 1 + \frac{2M \tilde{D} \Psi}{p}) + \left( \frac{a_1}{p} + a_2 \right) M \tilde{D}
\]

(8)

Next, we defuzzify \( E[TTC] \) by using the signed distance method. The signed distance of \( E[TTC] \) is given by

\[
d(\tilde{D}, \tilde{0}) = \frac{M (\tilde{D}, \tilde{0})}{nQ} (A + nF) + MS (\tilde{D}, \tilde{0}) + \frac{M (\tilde{D}, \tilde{0}) S_b}{Q} + Mz_v (\tilde{D}, \tilde{0}) - z_v (\tilde{D}, \tilde{0})
\]

\[
+ h_b \left( \frac{MQ (\tilde{D}, \tilde{0})}{x} - \frac{Q (\tilde{D}, \tilde{0})}{x} + \frac{[1 - E(Y)]Q}{2} + k_1 \sigma \sqrt{Q/p + T_w} \right)
\]

\[
+ \left( \frac{M \pi (\tilde{D}, \tilde{0}) \sigma}{nQ} \right) \left( \sqrt{Q/p + T_w} \Psi (k_1) + (n - 1) \sqrt{T_w} \Psi (k_2) \right) + \frac{M (\tilde{D}, \tilde{0}) K}{Q} + Mw (\tilde{D}, \tilde{0})
\]

\[
- w (\tilde{D}, \tilde{0})
\]

\[
+ \frac{M (\tilde{D}, \tilde{0}) S_b}{Q} + h_v \frac{Q}{2} (n \left[ 1 - \frac{M (\tilde{D}, \tilde{0})}{p} \right] - 1 + \frac{2M (\tilde{D}, \tilde{0})}{p}) + \left( \frac{a_1}{p} + a_2 \right) M (\tilde{D}, \tilde{0})
\]

(9)

Let \( \Psi \) be the family of all fuzzy sets \( \tilde{D} \) defined in \( R \) for which the \( \alpha \)-cut \( D(\alpha) = [D_L(\alpha), D_U(\alpha)] \) exists for every \( \alpha \in [0, 1] \). Both \( D_L(\alpha) \) and \( D_U(\alpha) \) are continuous functions in \( \alpha \in [0, 1] \). Then it can be said that for any \( \tilde{D} \in \Psi \), we have \( \tilde{D} = \bigcup_{\alpha \in [0, 1]} [D_L(\alpha), D_U(\alpha)] \). Hence, for \( \tilde{D} \in \Psi \) the signed distance from \( \tilde{D} \) to \( \tilde{0} \) can be defined as:

\[
d(\tilde{D}, \tilde{0}) = \frac{1}{2} \int_0^1 (D_L(\alpha) + D_U(\alpha)) d\alpha.
\]

For a triangular fuzzy number \( \tilde{D} = (a, b, c) \), the \( \alpha \)-cut of \( \tilde{D} \) is \( D(\alpha) = [D_L(\alpha), D_U(\alpha)] \) for \( \alpha \in [0, 1] \), where \( D_L(\alpha) = a + (b - a) \alpha \) and \( D_U(\alpha) = c - (c - b) \alpha \). The signed distance from \( \tilde{D} \) to \( \tilde{0} \) is:

\[
d(\tilde{D}, \tilde{0}) = \frac{1}{4} \left( a + 2b + c \right).
\]

\[
= \frac{1}{4} \left[ ((Dz_c) + 2D + (Dz_0)) = D + \frac{1}{4} (z_c, z_0) \right.
\]

(10)

Therefore, the expected total cost for supply chain is can be rewritten as follows:

\[
d(\tilde{D}, \tilde{0}) = \frac{M (\tilde{D}, \tilde{0}) (z_{z - z_1})}{nQ} (A + nF) + MS \left( \frac{D}{4} [z_{z - z_1}] \right) + \frac{M (\tilde{D}, \tilde{0}) S_b}{Q} + Mz_v \left( \frac{D}{4} [z_{z - z_1}] \right)
\]

\[
- z_v \left( \frac{D}{4} [z_{z - z_1}] \right) + \left( \frac{a_1}{p} + a_2 \right) M \left( \frac{D}{4} [z_{z - z_1}] \right) + \frac{M (\tilde{D}, \tilde{0}) K}{Q} + Mw \left( \frac{D}{4} [z_{z - z_1}] \right)
\]

\[
+ h_b \left( \frac{MQ (\tilde{D}, \tilde{0})}{x} - \frac{Q (\tilde{D}, \tilde{0})}{x} + \frac{[1 - E(Y)]Q}{2} + k_1 \sigma \sqrt{Q/p + T_w} \right)
\]

4
\[ + \left( \frac{M\pi D + \frac{1}{4} [z_2 - z_1]}{nQ} \right) \left( \sqrt{\frac{Q}{p} + T_w \psi (k_1) + (n-1)\sqrt{T_w \psi (k_2)}} \right) \]
\[ + \frac{M \left( \frac{1}{4} [z_2 - z_1] \right) S_v}{Q} + h_v \left( \frac{Q}{2} \right) \left[ 1 - \frac{M \left( \frac{1}{4} [z_2 - z_1] \right)}{p} \right] - 1 + \frac{2M \left( \frac{1}{4} [z_2 - z_1] \right)}{p} \]
\[ + Mw \left( \frac{1}{4} [z_2 - z_1] \right) - w \left( \frac{1}{4} [z_2 - z_1] \right) \]

(11)

4. Solution methodology

By considering a fixed value of \( n \), the minimum value of the above expected total cost for supply chain occurs at the point \( (n, Q, k, P) \) which satisfies \( \frac{\partial EJTC(n, Q, k, P)}{\partial k} = 0 \) and \( \frac{\partial EJTC(n, Q, k, P)}{\partial P} = 0 \) simultaneously. To find the solution of the problem, we first find the first partial derivative of \( EJTC(n, Q, k, P) \) with respect to \( k \) and \( Q \) and \( P \), respectively and set the equations to zero, so we will follow the following expressions:

\[ 1 - F_s(k_1) + (n-1) \left[ 1 - F_s \left( k_1 \frac{Q/p + T_w \psi (k_1)}{\tau_s} \right) \right] = \frac{h_b n Q}{\pi D} \]

(12)

\[ Q = \sqrt{\frac{2M \left( \frac{1}{4} [z_2 - z_1] \right) \left( \frac{A+k}{n} + F \right) + S_b + S_v + \frac{\pi n (Q/p + T_w \psi (k_1) + (n-1)\sqrt{T_w \psi (k_2)})}{n + h_v \left( \frac{Q}{2} \right) \left[ 1 - \frac{M \left( \frac{1}{4} [z_2 - z_1] \right)}{p} \right] - 1 + \frac{2M \left( \frac{1}{4} [z_2 - z_1] \right)}{p} \right] + h_b [1 - E(Y)] + \frac{2h_b M \left( \frac{1}{4} [z_2 - z_1] \right)}{n p Q (Q/p + T_w)}} \]

(13)

\[ P = \sqrt{\frac{a_1 M \left( \frac{1}{4} [z_2 - z_1] \right) + M Q h_v \left( \frac{1}{4} [z_2 - z_1] \right) - \frac{M Q h_v n (D+\frac{1}{4} [z_2 - z_1])}{2} + \frac{h_b k_i}{2 \sqrt{Q/p + T_w}}}{a_2 M \left( \frac{1}{4} [z_2 - z_1] \right) + \frac{M \left( \frac{1}{4} [z_2 - z_1] \right) \psi (k_i)}{2 \sqrt{Q/p + T_w}}} \]

(14)

Here, we propose an iterative procedure to obtain the optimal decision variables, which is

1. Fuzzify \( D \) to be a triangular fuzzy number, \( \tilde{D} = (D-z_i, D, D+z_i) \), where \( z_i \) for \( i=1,2 \) are decided by the decision makers. Then, defuzzify the fuzzy number \( \tilde{D} \) by using the signed distance method
2. Set \( n=1 \) and \( EJTC(n-1, Q, k, P) = \infty \)
3. Set the initial values of \( Q \) and \( P \) with equations (13) and (14) by setting the stochastic variables equal to zero
4. Compute \( k_i \) by substituting \( Q \) into equation (12).
5. Compute \( P \) from equation (14).
6. For a given previous value of \( k_i \) and \( P \), compute \( Q \) from equation (13).
7. Compute \( k_i \) by substituting \( Q \) into equation (12).
8. Repeat steps 3 - 6 until no change occurs in the values of \( Q \), \( k_i \) and \( P \).
9. Set \( Q_i = Q, k_{i+1} = k_i \) and \( P_i = P \) and compute \( EJTC(n, Q, k, P) \) from equation (11).
10. If \( EJTC(n, Q, k, P) \leq EJTC(n-1, Q, k, P) \), repeat steps 2-8 with \( n=n+1 \), otherwise go to step 11.
11. Compute 

$$EJTC(n^*, Q^*, k^*, P^*) = EJTC(n-1, Q_{n-1}, k_{n-1}, P_{n-1})$$

then 

$$n^*, Q^*, k^*, P^*$$

are the optimal solution.

5. Numerical example

Let us consider a supply chain inventory model consisting of a vendor and a buyer with the following data: 

- Demand rate ($D$): 1,000 units/year,
- Ordering cost ($C_o$): $100/order,
- Setup cost ($C_s$): $400/setup,
- Lead time ($L$): 25 units/year,
- Purchase price ($P$): $50/unit,
- Maximum lead time ($L_{max}$): 5,000 units/year,
- Minimum lead time ($L_{min}$): 1,000 units/year,
- Probability density function for the percentage of defectives is taken to be

$$f(y) = \begin{cases} 
25, & 0 \leq y \leq 0.04 \\
0, & \text{otherwise} 
\end{cases}$$

Therefore, we will have

$$E(Y) = \int_0^{0.04} 25 y dy = 0.02$$

and

$$E\left(\frac{1}{1-y}\right) = \int_0^{0.04} \frac{25}{1-y} dy = 1.02055.$$ 

The optimal values of 

$$n^*, k^*, Q^*, \text{ and } P^*$$

satisfying the proposed solution procedure, are 7 deliveries, 2,0659, 191 units and 2,296 units which can minimize the value of $JTC$ at $4,944.6$.

6. Conclusions

In this paper, an integrated inventory model for single-vendor single-buyer under fuzzy annual demand and imperfect items was proposed. The demand was assumed to be normally distributed and the lead time was taken to be variable and dependent upon ordering size and production rate. A simple algorithm was suggested to obtain the model’s solutions. The proposed model can help the practitioners to keep the vendor-buyer inventories more efficiently. It can assist managers to decide the optimum ordering quantity, safety factor, number of deliveries and level of production rate. Furthermore, it may also give guidance to managers to reduce the risk of defective rate by altering the ordering quantity. Further research can look into considering many aspects, such as vendor’s recovery process, inspection errors, multi-stage supply chain system and learning curve.

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