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Integrated Fuzzy Inventory Model with Minimal Repair

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Abstract.

In this study, we propose an integrated inventory model, which is under fuzzy demand condition. Additionally, we consider maintenance in the model. There are two types of preventive maintenance, namely perfect preventive maintenance and imperfect preventive maintenance. If failure occurs, the minimal repair can restore the system to working order. During the competitive market today, the inventory policy is an important issue to the supply chain management. Therefore, the purpose of this paper is to build an integrated inventory model with minimal repair in a fuzzy environment to reflect real world situation. Numerical examples are given to illustrate the application of the model.

1. Introduction

The inventory management has a great importance in the supply chain management now-a-days. In other words, the performance of the supply chain can be affected by the inventory policy easily. Jammernegg and Reiner [1] mentioned that the efficient inventory policy can enhance performance of supply chain. Olson and Xie [2] proposed that vendor and buyer should use the same inventory system to cooperate with each other, and firms might have great loss by using the improper inventory policy. According to above papers, the appropriate inventory policy is an essential part in the supply chain. In this study, we would like to develop an integrated inventory model and discuss how it works under different preventive maintenance conditions.

In order to conduct the JIT productive system, the upstream and downstream suppliers need to be integrated closely. Also, the vendors and buyers need strong cooperation to have a better performance. The first integrated inventory model was proposed by Goyal [3]. He assumed that the supplier's production cycle time is an integer multiple of the customer's order time interval. Banerjee [4] develop a joint economic-lot-size model which is under a vendor and a purchaser with lot-for-lot production policy by extension

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Goyal's model. After that, Goyal [5] also extended Banerjee's model. He relaxed the lot-for-lot policy and considered that vendor's economic production quantity is supposed to be an integer multiple of the buyer's purchase quantity. It is a significant contribution for the integrated model to improve the relationship between vendors and buyers.

Pan [6] proposed a model with fuzzy annual demand and the production rate. The author also employed the signed distance and a ranking method for fuzzy numbers to find the estimate of the common total cost in the fuzzy sense. Chiu et al. [7] suggested the fuzzy multi-objective integrated logistics model with the transportation cost and demand fuzziness to solve green supply chain problems. Yang [8] formulated a three-echelon integrated model under defective products, reworking and credit period consideration. He also considered fuzzy demand in the integrated model to deal with the uncertainty of demand in real life.

To encounter the daily challenge and be more advantages, manufactures require a production and inventory policy. Recently, maintenance is considered to an important aspect of production. Barlow and Hunter [9] proposed a paper of preventive maintenance (PM) to keep the production system efficient by regular maintenance. Sheu et al. [10] pointed that maintenance is launched when equipment fails or as planned preventive maintenance (PM). Yang et al. [11] considered that the product system can be produced more efficiently using a PM program that significantly increased production process reliability. Groenevelt et al. [12] present that the production of equipment could be repaired immediately when production system shut down. They assumed two production control policies for coping with these randomly interferences. The first policy supposes that after a breakdown, production of the interrupted lots is not resumed. Instead, the on-hand inventory is depleted before a new cycle restart. In the second policy, if the current on-hand inventory is under a certain threshold level, production is resumed immediately after a failure occurs. Tseng [13] launched the paper about a perfect maintenance policy which can increase the reliability of the system. Following maintenance, perfect PM models assume that the system to be as good as new".

With above discussion, we would like to build an integrated inventory model with minimal repair. Hence, we determine demand based on fuzzy theory because of the uncertain environments. Finally, we can try to determine a better inventory policy with preventive maintenance condition.

2. Notations and Assumptions

This study is based on the cost allocation of the integrated inventory model [14]. To establish the proposed model, the following notations and assumption are used.

C_{pm} cost of each PM.

C_m minimal repair cost at each failure.

C_h inventory cost rate per unit per year.

C_o purchaser's ordering cost.

C_p purchaser's purchase cost per unit.

C_s vendor's setup cost.

C_v vendor's production cost per unit.

m integer number of lots of items delivered from vendor to purchaser.

D average demand per year.

$\overline{P}_j$ probability of j PM is imperfect maintenance.

P_j probability of j PM is perfect maintenance which follows the $(j-1)$ imperfect PM: $P_j = \overline{P}_{j-1} - \overline{P}_j$.

P production rate, $P > D$.

Q order quantity.

Q_d number of non-reworkable defective products at each failure.

r breakdown rate of unit.

T time of inventory cycle.

Assumptions.

(1) In this study, the constants which are setup cost, ordering cost and holding cost are known.

(2) The original system begins operating at time 0. The production process begins in an in-control state and produces perfect items.

(3) Setup cost C_s is incurred at the start of each inventory cycle. PM is performed following the production run period. The cost of each PM is C_{pm}.

(4) A system has two types of PM at cumulative production run time j, T $(j = 1, 2, 3, \ldots)$, based on outcome.

- Type-I PM (imperfect PM) results in the system having the same failure rate as before PM, with probability $\overline{P}_j$.
- Type-II PM (perfect PM) makes the system as good as new, with probability $P_j = P_{j-1} - \overline{P}_j$.

(5) Following a perfect PM, the system returns to age 0.

(6) If failure occurs before the scheduled PM, the system shifts the "out-of-control" state, then minimal repair can be made immediately. Minimal repair merely restores the system to a functioning state following failure, so the production process returns to the in-control condition.

(7) The repair times are negligible.

(8) The PM cycle and inventory cycle are assumed to be same in this paper.

(9) The imperfect products will completely and immediately fix.

(10) The time horizon is infinite.

3. Model Formulation

Based on the above notations and assumption, the joint total expected annual cost is the following:

$$JTEC(T,m)=\frac{C_s}{T}+\frac{C_{pm}}{T}+\frac{TD}{2m}C_hC_v\Big[\Big(m\Big(1-\frac{D}{P}\Big)-1+\frac{2D}{P}\Big)\Big] + \Big[\Big(\frac{C_m}{T}-\frac{C_hQ_d}{2}\Big)\sum_{j=1}^{\infty}\frac{\overline{P}_{j-1}-\overline{P}_j}{\sum_{j=1}^{\infty}\overline{P}_{j-1}}\int_0^{j(\frac{D}{P})T}r(t)dt\Big]+\frac{C_om}{T}+C_hC_P\frac{TD}{2m}. \tag{1}$$

This study assumes that demand D is a triangular fuzzy number, where $D=(D-\Delta_1,2D,D+\Delta_2),0<\Delta_1<D,0<\Delta_2)$, and Δ_1 Δ_2 are both determined by decision-makers. In this case, the joint total expected annual cost is a fuzzy function and can be expressed as:

$$\widetilde{W}(T,m)=\frac{C_s}{T}+\frac{C_{pm}}{T}+\frac{T\widetilde{D}}{2m}C_hC_v\Big[\Big(m\Big(1-\frac{\widetilde{D}}{P}\Big)-1+\frac{2\widetilde{D}}{P}\Big)\Big] + \Big[\Big(\frac{C_m}{T}-\frac{C_hQ_d}{2}\Big)\sum_{j=1}^{\infty}\frac{\overline{P}_{j-1}-\overline{P}_j}{\sum_{j=1}^{\infty}\overline{P}_{j-1}}\int_0^{j(\frac{D}{P})T}r(t)dt\Big]+\frac{C_om}{T}+C_hC_P\frac{T\widetilde{D}}{2m}. \tag{2}$$

Theorem 1. From Zimmermann [15] and Yao and Wu [16] for a fuzzy set $\tilde{A}\in\Omega$ and $\alpha\in[0,1]$, the α-cut of the fuzzy set $\tilde{A}$ is $A(\alpha)=\{x\in\Omega\mid\mu_A(x)\geq\alpha\}=[A_L(\alpha),A_U(\alpha)]$, where $A_L(\alpha)=a+(b-a)\alpha$ and $A_U(\alpha)=c-(c-b)\alpha$ use this method to defuzzify, which is called the sign distance of $\tilde{A}$ to $\tilde{0}_1$:

$$\begin{aligned} d(\tilde{A},\tilde{0}_1)&=\int_0^1 d([A_L(\alpha)_\alpha,A_U(\alpha)_\alpha],\tilde{0}_1)dx\\ &=\frac{1}{2}\int_0^1(A_L(\alpha)+A_U(\alpha))dx\\ &=\frac{1}{4}(2b+a+c) \end{aligned} \tag{3}$$

$\widetilde{D}$ is obtained by Theorem 1:

$$d(\widetilde{D},\tilde{0}_1)=\frac{1}{4}[(D-\Delta_1)+2D+(D+\Delta_2)]=D+\frac{1}{4}(\Delta_2-\Delta_1). \tag{4}$$

Next, defuzzify $\widetilde{W}(T,m)$ by using the signed distance method. The signed distance of $\widetilde{W}$ to $\tilde{0}_1$ is given by:

$$d(\widetilde{D},\tilde{0}_1)=\frac{C_s}{T}+\frac{C_{pm}}{T}+\frac{Td(\widetilde{D},\tilde{0}_1)}{2m}C_hC_v\Big[\Big(m\Big(1-\frac{d(\widetilde{D},\tilde{0}_1)}{P}\Big)-1+\frac{2d(\widetilde{D},\tilde{0}_1)}{P}\Big)\Big] + \Big[\Big(\frac{C_m}{T}-\frac{C_hQ_d}{2}\Big)\sum_{j=1}^{\infty}\frac{\overline{P}_{j-1}-\overline{P}_j}{\sum_{j=1}^{\infty}\overline{P}_{j-1}}\int_0^{j(\frac{d(\widetilde{D},\tilde{0}_1)}{P})T}r(t)dt\Big]+\frac{C_om}{T}$$

$$+C_h C_P \frac{Td(\widetilde{D}, \tilde{0}_1)}{2m}. \tag{5}$$

Substituting the result of (4) into (2), we have

$$\begin{aligned}\widetilde{W}(T,m) =& \frac{C_s}{T} + \frac{C_{pm}}{T} \\ &+ \frac{T(D+\frac{1}{4}(\Delta_2-\Delta_1))}{2m} C_h C_v \Big[\Big(m\Big(1 - \frac{(D+\frac{1}{4}(\Delta_2-\Delta_1))}{P}\Big) \\ &- 1 + \frac{2(D+\frac{1}{4}(\Delta_2-\Delta_1))}{P}\Big)\Big] \\ &+ \Big[\Big(\frac{C_m}{T} - \frac{C_h Q_d}{2}\Big) \sum_{j=1}^{\infty} \frac{\overline{P}_{j-1} - \overline{P}_j}{\sum_{j=1}^{\infty} \overline{P}_{j-1}} \int_0^{j(\frac{(D+\frac{1}{4}(\Delta_2-\Delta_1))}{P})T} r(t)dt\Big] + \frac{C_o m}{T} \\ &+ C_h C_P \frac{T(D+\frac{1}{4}(\Delta_2-\Delta_1))}{2m}.\end{aligned} \tag{6}$$

where $\widetilde{W}(T,m)$ is considered as the estimated joint expected to total cost in fuzzy linguistic.

The objective of the estimated joint expected annual total cost is to determine the optimal inventory runs time T and the integer number of lots delivered from vendor to purchaser, bringing $\widetilde{W}(T,m)$ to a minimum value. Utilizing classical optimization, we take the first and second derivatives of $\widetilde{W}(T,m)$ with respect to T, and obtain

$$\begin{aligned}\frac{\partial \widetilde{W}(T,m)}{\partial T} =& -\frac{\Big(C_o m + C_s + C_{pm} + \Big[C_m \sum_{j=1}^{\infty} \frac{\overline{P}_{j-1} - \overline{P}_j}{\sum_{j=1}^{\infty} \overline{P}_{j-1}} \int_0^{j(\frac{\widetilde{D}}{P})T} r(t)dt\Big]\Big)}{T^2} \\ &+ \Big[\Big(\frac{C_m}{T} - \frac{C_h Q_d}{2}\Big) \sum_{j=1}^{\infty} \frac{\overline{P}_{j-1} - \overline{P}_j}{\sum_{j=1}^{\infty} \overline{P}_{j-1}} j \frac{\widetilde{D}}{P} r(jT(\frac{\widetilde{D}}{P}))\Big] + \frac{C_h C_P \widetilde{D}}{2m} \\ &+ \frac{C_h C_v \widetilde{D}}{2m} \Big[m\Big(1 - \frac{\widetilde{D}}{P}\Big) - 1 + \frac{2\widetilde{D}}{P}\Big]\end{aligned} \tag{7}$$

let

$$\sum_{j=1}^{\infty} \frac{\overline{P}_{j-1} - \overline{P}_j}{\sum_{j=1}^{\infty} \overline{P}_{j-1}} \int_0^{j(\frac{\widetilde{D}}{P})T} r(t)dt = Z$$

and

$$\begin{aligned}\frac{\partial \widetilde{W}(T,m)}{\partial T} =& -\frac{(C_o m + C_s + C_{pm} + C_m \times Z)}{T^2} + \Big[\Big(\frac{C_m}{T} - \frac{C_h Q_d}{2}\Big) Z'\Big] + \frac{C_h C_P \widetilde{D}}{2m} \\ &+ \frac{C_h C_v \widetilde{D}}{2m} \Big[m\Big(1 - \frac{\widetilde{D}}{P}\Big) - 1 + \frac{2\widetilde{D}}{P}\Big]\end{aligned} \tag{8}$$

and

$$\frac{\partial^2 \widetilde{W}(T,m)}{\partial T^2} = \frac{2(C_o m + C_s + C_{pm})}{T^3} - \frac{C_h Q_d Z''}{2}. \tag{9}$$

Since $(\partial^2 \widetilde{W}(T,m))/(\partial T^2) > 0$, $W(T,m)$ is convex in T, and the minimum value of $W(T,m)$ will occur at the point that satisfies $(\partial^2 \widetilde{W}(T,m))/(\partial T^2) = 0$. Setting (6) equal to zero and solving for T.

In the above formula $\widetilde{D} = D + \frac{1}{4}(\Delta_2 - \Delta_1)$.

4. Numerical Examples

To illustrate the effectiveness of the proposed models, consider an inventory situation with the following data adopted in Yang (2018): average demand $D = 600$ unit/year, production rate $P = 1000$ unit/year, inventory cost rate $C_h = 0.2$/unit, vendor's production cost $C_v = \$20$/unit, purchaser's purchase cost $C_P = \$25$/unit, purchaser's ordering cost $C_o = \$20$/unit, vendor's setup cost $C_s = \$20$/unit, cost of each PM $C_{pm} = \$20$/run, minimal repair cost $C_m = \$10$/time, number of non-reworkable defective products at each failure $Q_d = 1$, breakdown rate $r(t)$ following a uniform distribution with $a = 0.1$, $b = 0.4$.

Based on the above data and the model proposed in this article, we are trying to find out an optimal value of T and m, and find the optimal joint total expected annual cost $W(T,m)$ in the fuzzy sense for various given sets of Δ_1 and Δ_2. Note that in practical situations, Δ_1 and Δ_2 are determined by the decision-makers due to the uncertainty of the problem. We use the following steps so that we can find the optimal values of T and m.

Step 1. obtain Δ_1 and Δ_2 from decision-maker.

Step 2. Calculate T using relation.

Step 3. Calculate $JTEC$ by embedding the late calculates T and m.

Step 4. Find the minimum $JTEC$ and the corresponding value of decision variables T^* and m as the optimal solution. The results are illustrated as follows.

The results are summarized in following tables.

Table 1: Data of $m = 1$.

$m=1$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*,m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.171201692	819.2479	-0.014	0.013
100	200	(500,600,800)	0.16888066	830.0745	-0.027	0.027
150	300	(450,600,900)	0.166628855	840.8651	-0.04	0.04
300	300	(300,600,900)	0.173595473	808.3839	0	0
300	150	(300,600,750)	0.18125256	775.5509	0.044	-0.041
200	100	(400,600,700)	0.178616689	786.5371	0.029	-0.027
100	50	(500,600,750)	0.176065784	797.4808	0.014	-0.013

According to the above tables, we can get the optimal inventory runs time T_c^*, and the optimal joint total expected annual cost $W(T_c^*)$ of the original model when $\Delta_1 =$

Table 2: Data of $m = 2$.

$m = 2$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*, m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.249704159	724.3006	-0.011	0.01
100	200	(500,600,800)	0.247108565	731.4599	-0.021	0.02
150	300	(450,600,900)	0.244589992	738.5481	-0.031	0.03
300	300	(300,600,900)	0.252380777	717.0681	0	0
300	150	(300,600,750)	0.260941449	694.9073	0.034	-0.03
200	100	(400,600,700)	0.257994616	702.3739	0.022	-0.02
100	50	(500,600,750)	0.255142721	709.76	0.011	-0.01

Table 3: Data of $m = 3$.

$m = 3$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*, m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.313003389	708.27	-0.008	0.008
100	200	(500,600,800)	0.310459238	713.6171	-0.016	0.015
150	300	(450,600,900)	0.308001899	718.858	-0.024	0.023
300	300	(300,600,900)	0.315638795	702.8142	0	0
300	150	(300,600,750)	0.324142201	685.7676*	0.027	-0.024
200	100	(400,600,700)	0.321202855	691.5659	0.018	-0.016
100	50	(500,600,750)	0.318370236	697.2471	0.009	-0.008

Table 4: Data of $m = 4$.

$m = 4$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*, m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.367987537	713.9059	-0.007	0.006
100	200	(500,600,800)	0.365625894	718.0566	-0.013	0.012
150	300	(450,600,900)	0.363365426	722.0672	-0.019	0.038
300	300	(300,600,900)	0.370455075	709.6128	0	0
300	150	(300,600,750)	0.378546045	695.8508	0.022	-0.019
200	100	(400,600,700)	0.375728607	700.5881	0.014	-0.013
100	50	(500,600,750)	0.373033599	705.1745	0.007	-0.006

$\Delta_2 = 600$. Furthermore, we use $V_T = \frac{T^* - T_c^*}{T_c^*} \times 100\%$ and $V_W = \frac{W(T^*, m^*) - W(T_c^*)}{W(T_c^*)} \times 100\%$, in order to compare the variation of the optimal inventory runs time and the optimal joint total expected annual cost between this fuzzy model and the original model.

From the above tables, we observe that:

(1) When $\Delta_1 < \Delta_2$, so $\widetilde{D} > D$. And then $T^* < T_c^*$, $W(T^*, m^*) > W(T_c^*)$. We can obtain $V_T < 0$ and $V_W > 0$.

Table 5: Data of $m = 5$.

$m = 5$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*, m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.417398915	728.0574	-0.005	0.005
100	200	(500,600,800)	0.415279375	731.3124	-0.01	0.009
150	300	(450,600,900)	0.413279135	734.3954	-0.015	0.013
300	300	(300,600,900)	0.41964252	724.7664	0	0
300	150	(300,600,750)	0.427171853	713.2671	0.018	-0.016
200	100	(400,600,700)	0.424523104	717.2357	0.012	-0.01
100	50	(500,600,750)	0.422015371	721.0217	0.006	-0.005

Table 6: Data of $m = 6$.

$m = 6$						
Δ_1	Δ_2	$\widetilde{D}$	T^*	$W(T^*, m^*)$	$V_T(\%)$	$V_W(\%)$
50	100	(550,600,700)	0.462702918	746.0951	-0.004	0.004
100	200	(500,600,800)	0.460852827	748.6313	-0.008	0.007
150	300	(450,600,900)	0.459142838	750.9653	-0.012	0.01
300	300	(300,600,900)	0.464697692	743.3544	0	0
300	150	(300,600,750)	0.47160326	733.8816	0.015	-0.013
200	100	(400,600,700)	0.469142016	737.2503	0.01	-0.008
100	50	(500,600,750)	0.466842202	740.407	0.005	-0.004

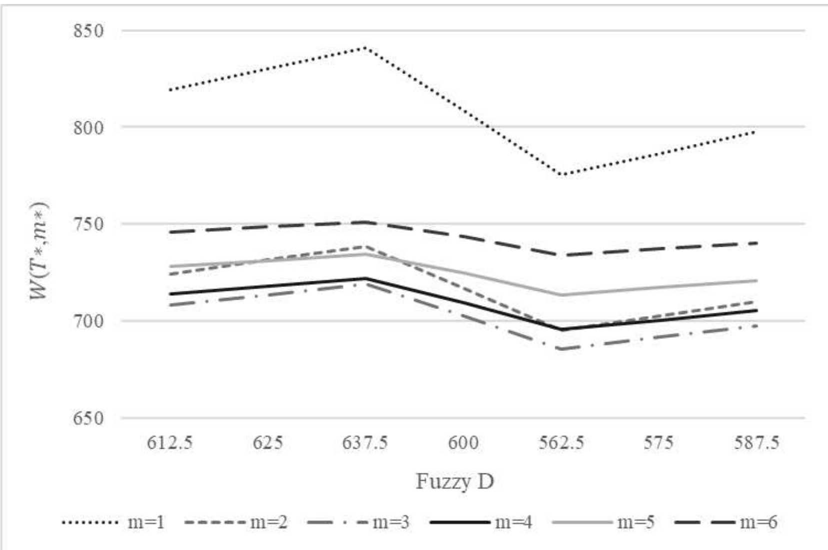

Figure 1: The mathematical relationship diagram of $JTEC$ and $\widetilde{D}$.

(2) When $\Delta_1 = \Delta_2$, $\widetilde{D} = D = 600$. In this case, the fuzzy model will be same as the original model.

(3) $W(T^*, m^*)$ increases while $\Delta_2 - \Delta_1$ increases and m decreases.

(4) According to the result, the minimum of $JTEC$ will occur when $m = 3$, and $W(T_c^*) = 685.7676$, $T_c^* = 0.324142201$.

5. Conclusion

There are many uncertainties in today's supply chain market. Therefore, a well-designed supply chain network is crucial. In this study, the consideration of the lack of historical data to determine the annual demand, we assume the demand quantity as a triangle fuzzy number. Owing to different upper and lower limits of the demand, the decision-makers can obtain more flexibility. This method might make the theoretical model be closer to the real situation. Through the numerical example in this study, the results show that if $\widetilde{D}$ increases, $JTEC$ will increases. Further, the minimum value of $JTEC$ don't occur when $\Delta_1 = \Delta_2$, $\widetilde{D} = D = 600$. In the future, the integrated inventory model will be hopefully added different fuzzy factor, to simulate the realistic world application in the supply chain environment.

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