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A production/recycling model with stationary demand and return rates

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Abstract

A production-recycling system is investigated. A constant demand can be satisfied with production and recycling. The used items are bought back and then recycled. The not recycled products are disposed off. It is analyzed two types of models. The first model examines the EOQ related costs and minimizes the relevant costs. The second model generalizes the first model with introduction of the cost function with linear waste disposal, recycling, production and buyback costs. It is asked whether the pure (either production or recycling) or mixed strategies are optimal.

Keywords: EOQ model, Production, Recycling, Waste disposal, Cost minimization

Összefoglalás

Egy termelési-recycling modellt vizsgál a dolgozat. A stacionárius keresletet termelésből vagy újrafelhasználásból lehet kielégíteni. A recyclinghoz a használt anyagokat előbb visszavásárolja a gyártó, majd azokat újrafeldolgozza. A visszavásárolt, de fel nem használt anyagokat hulladékként kezelik vagy deponálják. Két modell típus kerül bemutatásra. Az első modellben a készlettartási és rendelési költségeket minimalizáljuk. A második modellben a készletezési költségeken túl lineáris hulladékkezelési, újrafelhasználási, termelési és visszavásárlási költségeket is figyelembe vesszük. Azt vizsgáljuk, hogy a tiszta, azaz vagy termelés vagy újrafelhasználás, vagy a kevert, azaz termelés és újrafelhasználás, stratágiák optimálisak-e.

Kulcsszavak: Tételnagyság modell, Termelés, Újrafelhasználás, Hulladékkezelés, Költségminimalizálás

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1. Introduction

In this paper a model of the EOQ type is developed and analyzed, in which a producer serves a stationary product demand occurring at the rate $D > 0$. This demand is served by producing or procuring new items as well as by recycling some part $0 \le \delta \le 1$ of the used products coming backing to the producer at a constant return rate $d = \alpha D, 0 \le \alpha \le 1$. The parameters δ and α are called *marginal use rate* and *marginal return rate*, respectively. The remaining part of the non-serviceable products $(1-\delta)d$ will be disposed off. $(1-\delta)$ is called *marginal disposal rate.*

First, an analysis of the situation is provided. The inventory stocks for *serviceable* products from the *production and recycling processes* (PRP) and for the *non-serviceable* items are determined. On the basis of these results the lot sizes and cycle times for the PRP can be found which minimize the per time unit total set-up and holding cost. This results in the explicit determination of a function $C_I(\alpha,\delta)$ which expresses these minimal cost as function of the marginal use and buyback rates.

Secondly, if linear waste disposal, production, recycling and buyback costs are introduced, the problem appears at which δ and α the total set-up, holding and linear costs $C_I(\alpha,\delta)+C_N(\alpha,\delta)$ is minimal. In this formulation the producer makes decision about how many of the used items to buy back for recycling.

A deterministic EOQ-type reverse logistic model was first analyzed by Schrady [10]. He has examined a model with more than one recycling cycles and one production/procurement cycle. He has calculated the optimal lot sizes to his model. Nahmias and Rivera [5] have generalized this model for the case of finite recycling rate. These authors have not investigated the optimal use and return rates. In these models all returned items are reusable. Richter [6,7,8], Richter and Dobos [9] and Dobos and Richter [1] have investigated a waste disposal model, where the return rate is a decision variable. They have given the optimal number of remanufacturing and production batches in dependence on the return rate. In paper of Richter [8] has examined the optimal inventory holding policy, if the waste diposal (return) rate is a decision variable. The result of this paper is that the optimal policy has an extremal property: either reuse all items without diposal or dispose off all items and produce new products. Teunter [11] has offered a model, where not all items can be remanufactured, i.e. the decision maker decides about the reuse of returned items.

2. Parameters and functioning of the system

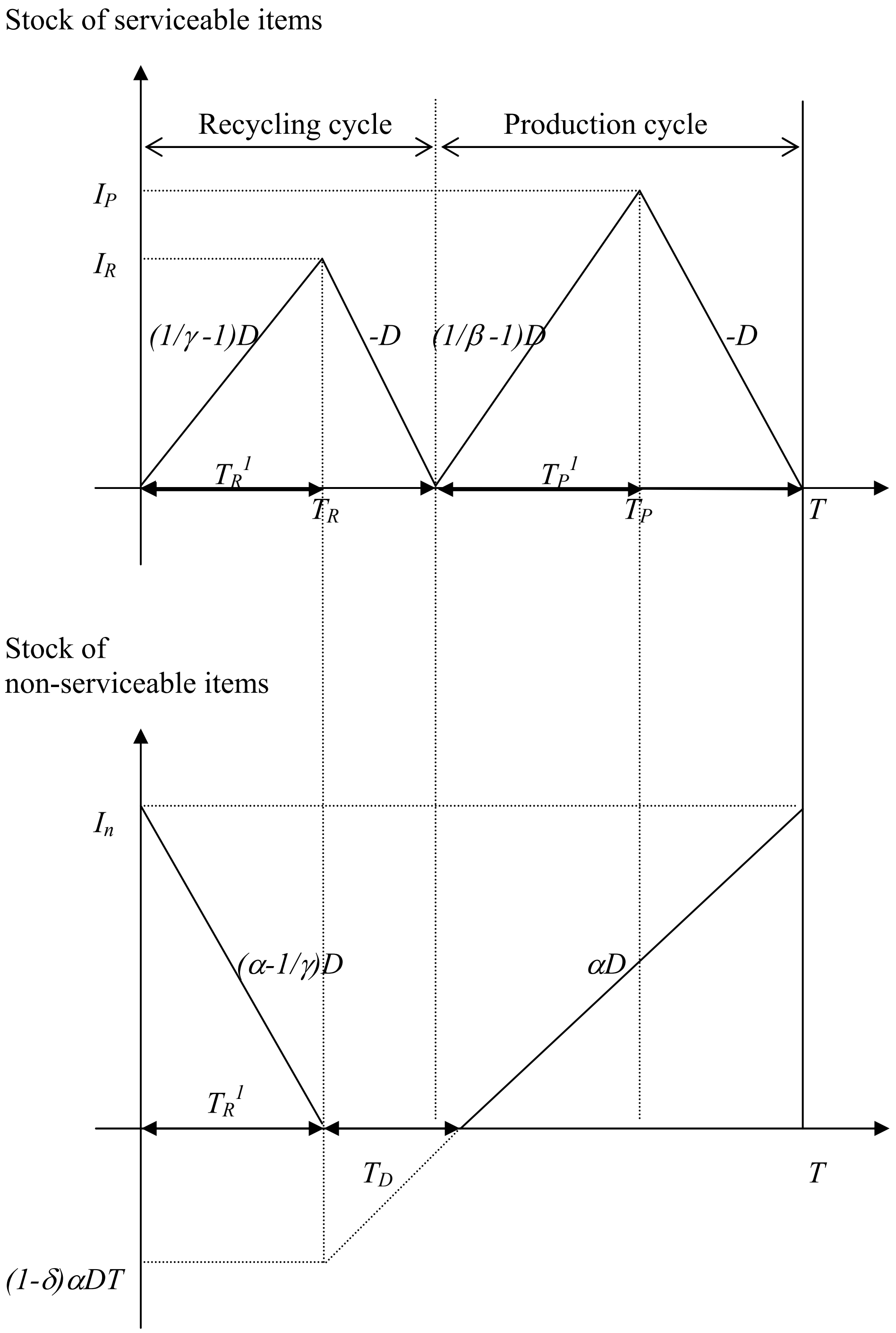
To model the production-recycling we use the following parameters and decision variables.

Lot-size related parameters of the model:

- D	demand rate,
- $P=\frac{1}{\beta}D$	production rate ($\beta < 1$),
- $d=\alpha D$	buyback rate ($0 \le \alpha \le 1$),
- $R=\frac{1}{\gamma}D$	recycling rate ($\gamma < 1$),
- S_R	setup costs of recycling,

- S_P setup costs of production,
- $S = S_R + S_P$ total setup costs,
- h_s holding cost of serviceable items,
- h_n holding cost of non-serviceable items.

Figure 1. Inventory status in the model



Lot-size independent cost parameters:

- C_w waste disposal cost for $(1-\delta)\cdot\alpha d\cdot T$,
- C_P linear production cost for $(1-\delta\alpha)d\cdot T$,
- C_R linear recycling cost for $\delta\cdot\alpha d\cdot T$,

- C_B buyback cost for $\alpha \cdot d \cdot T$.

Decision variables of the model:

- δ marginal use rate,
- α marginal buyback rate,
- T_R time interval of recycling,
- x_R recycling lot size, $x_R = D \cdot T_R$
- T_P time interval of production,
- x_P recycling lot size, $x_P = D \cdot T_P$
- T length of a production and recycling cycle.

Time period T_R the demand is satisfied by recycling the non-serviceable products stored until the end of T_R as well as the used products which continue to arrive at the rate $d < D = \alpha d$ (compare Fig. 1). Due to the given recycling rate $R > D = \gamma R$ the process of recycling lasts for some T_R^1 time units. When the recycling process is stopped the demand can be served by the accumulated stock of recycled products. Parameter of these figures T_R denotes the length of the *recycling cycle*.

After recycling the producer serves a demand of one product, which appears at a constant rate $D > 0$ The producer has to determine how much of new items to produce at a rate P, $D = \beta P < P$. Depending on this information he can found out how long he has to store the excess production. The time interval in which production and carrying new production is accomplished is called the *production cycle* and it is be denoted by T_P. The time interval $T = T_R + T_P$ gives the length of the *production and recycling cycle*.

The process of storing and disposing off non-serviceable goods can be organized in the following way: the $(1-\delta)dT$ units which have to be disposed during some interval T are disposed during the time *disposal interval* $T_D = (1-\delta)T$ just when they arrive. Hence some stock of non-serviceable items is set up during the *collection interval* $T_{RC} = T - T_D = \delta T$.

At the end of the production cycle the inventory stock of non-serviceable products attains its peak $I_n = (1-\delta)\, dT$ which is the initial inventory level at the beginning of the production and recycling cycle. At the end of the period T_R^1 the inventory stock of serviceable recycled products attains its peak $I_R = (1-\gamma)\, DT_R$. The peak of the inventory stock of newly produced items is $I_P = (1-\beta)\, DT_P$.

Example 1: For the case of parameters $D=2, P=3, R=3, \alpha=1/2, \delta=2/3, T_P=6$ the remaining parameters equal $T_R = 3, T = 9, T_{RC} = \delta T = 6, T_D = 3, I_P = 4, I_n = 4, I_R = 2$. (compare Fig. 1)

Example 2: Let the data of the previous example changed from $\delta = 2/3$ to $\delta = 1$, then $T_R = 6, T = 12, T_{RC} = \delta T = 12, T_D = 0, I_P = 4, I_n = 8, I_R = 4$ (compare Fig. 1)

3. Determination of the inventory cost

Let h_s denote the inventory cost for serviceable items per unit and time unit, and let h_n denote the same cost for non-serviceable items. If the length of the production and recycling cycle T is given the average inventory cost H_P, H_R, H_n for the newly produced items, recycled items and for the non-serviceable items, correspondingly, are as shown in Lemma 1. Let us now assume that the return rate α and the use rate δ are positive, i.e. there is recycling and the buyback and use rates are not equal to one, i.e. there is production, as well.

Lemma 1:

$$H_P = \frac{1}{2} T_P{}^2 \frac{P-D}{P} Dh_s = \frac{1}{2} DT^2 (1-\alpha\delta)^2 h_s (1-\beta). \tag{1}$$

$$H_R = \frac{1}{2} T_R^2 \frac{R-D}{R} Dh_s = \frac{1}{2} DT^2 \alpha^2 \delta^2 h_s (1-\gamma) \tag{2}$$

$$H_n = \frac{1}{2} T_{RC} I_n h_n = \frac{1}{2} DT^2 \alpha^2 \delta^2 h_n \left(\frac{1}{\alpha} - \gamma \right) \tag{3}$$

Proof. We will prove equality (1), the other cases can be proved in the same way. The total inventory holding costs for the produced items are the half of the multiplication of the peak inventory level and the length of the production cycle. The length of the production cycle is equal to *(1-αδ) T*, so

$$H_P = h_s \cdot \frac{1}{2} T_P \cdot (1-\beta) DT_P = \frac{1}{2} DT^2 (1-\alpha\delta)^2 h_s (1-\beta).$$

Lemma 2: The total inventory cost per time unit is

$$H_T = \frac{H_P + H_R + h_n}{T} = \frac{1}{2} TD \cdot V(\alpha, \delta) \tag{4}$$

with

$$V(\alpha,\delta) = (1-\alpha\delta)^2 h_s (1-\beta) + \alpha^2 \delta^2 h_s (1-\gamma) + \alpha^2 \delta^2 h_n \left(\frac{1}{\alpha} - \gamma \right) \tag{5}$$

Proof. Formulas (4) and (5) are obtained, if the cost and time parameters on the left-hand side of (4) are substituted by the expressions (1) – (3).

Example 3: Let $h_s = 12$ and $h_n = 3$. For the data of the example 1 $V(1/2,2/3) = \frac{64}{243} h_s + \frac{2}{243} h_s + \frac{4}{27} h_n = 8$ and $H_T = \frac{1}{2} \cdot T \cdot 2 \cdot 8 = 8T$ hold.

The function $V(\alpha, \delta)$ expresses the total inventory cost per time unit and per demand unit.

4. Total cost minimization for the cycle time

Let the setup cost S per production and recycling cycle as the sum of setup costs S_P and S_R for the production and the recycling, respectively, be given. Then the setup cost per time unit is

$$S_T = \frac{S}{T}.$$

The average inventory costs of the model $C(\alpha, \delta, T)$ can be written in the following form

$$C(\alpha,\delta,T)=\frac{S}{T}+\frac{1}{2}TD\cdot V(\alpha,\delta)\rightarrow \min \tag{6}$$

Because of the convexity of the cost function in the production and recycling cycle time the cost optimal cycle time is $T^{o}(\alpha,\delta)=\sqrt{\frac{2S}{D\cdot V(\alpha,\delta)}}$ (7)

and the minimal total setup and inventory cost per time unit is

$$C_I(\alpha,\delta)=\sqrt{2DS\cdot V(\alpha,\delta)}\,. \tag{8}$$

The optimal recycling and production cycle times are

$$T_R^{o}(\alpha,\delta)=\alpha\delta\sqrt{\frac{2S}{D\cdot V(\alpha,\delta)}}\,, \tag{9}$$

$$T_P^{o}(\alpha,\delta)=(1-\alpha\delta)\sqrt{\frac{2S}{D\cdot V(\alpha,\delta)}}\,. \tag{10}$$

The optimal lot sizes are

$$x_R^{o}(\alpha,\delta)=\alpha\delta\sqrt{\frac{2DS}{V(\alpha,\delta)}}\,, \tag{11}$$

$$x_P^{o}(\alpha,\delta)=(1-\alpha\delta)\sqrt{\frac{2DS}{V(\alpha,\delta)}}\,. \tag{12}$$

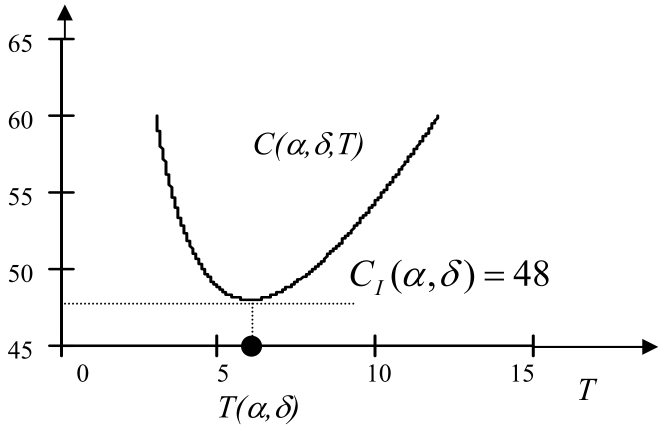
Example 4: Let as in examples 1 and 3 $D=2$, $P=3$, $R=3$, $\alpha=1/2$, $\delta=2/3$, $h_s=12$ and $h_n=3$, hence $d=1$, $\beta=\gamma=2/3$. It is known from Example 3 that $V(\alpha,\delta)=8$ and $H_T=8T$ hold. Setting $S=216$ the total cost per time unit is according to formula (7)

$$C\left(\frac{1}{2},\frac{2}{3},T\right)=\frac{216}{T}+\frac{1}{2}T\cdot 2\cdot 8=\frac{216}{T}+8T\,.$$

The cost curve is shown in Fig. 2.

The optimal length of the production cycle and of the recycling cycle is $T_P(\alpha,\delta)=\sqrt{\frac{2\cdot 216}{6\cdot 2}}=6$ and $T_R(\alpha,\delta)=3$, respectively. The lot sizes for production and recycling are given by $x_P=18$ and $x_R=9$. The minimal cost per time unit is $C_I\left(\frac{1}{2},\frac{2}{3}\right)=\frac{2}{3}\sqrt{2\cdot 216\cdot 2\cdot 6}=\frac{2\cdot 72}{3}=48$. Function $C_I(\alpha,\delta)$ is the minimal inventory holding costs in dependence on the marginal buyback and use rates.

Figure 2. Cost curve $C(\alpha,\delta,T)=\dfrac{216}{T}+8T$



Let us now investigate the two pure strategies: recycling and production (compare Figure 3.). If the return rate is zero, $\alpha = 0$, then there is no recycling. The total unit time costs for this model are, as in the textbooks

$$C(0,0,T)=\frac{S_P}{T}+\frac{D}{2}T\cdot h_s(1-\beta).$$

The optimal cycle time and lot size are

$$T_P^o(0,0)=\sqrt{\frac{2S_P}{D\cdot h_s(1-\beta)}},\tag{13}$$

$$x_P^o(0,0)=\sqrt{2DS_Ph_s(1-\beta)}.\tag{14}$$

In the case of no production it is assumed that the return and use rates are one: $\alpha = \delta = 1$. The cost function has the next form

$$C(1,1,T)=\frac{S_R}{T}+\frac{D}{2}T\cdot(h_s+h_n)(1-\gamma).$$

The optimal cycle time and lot size are

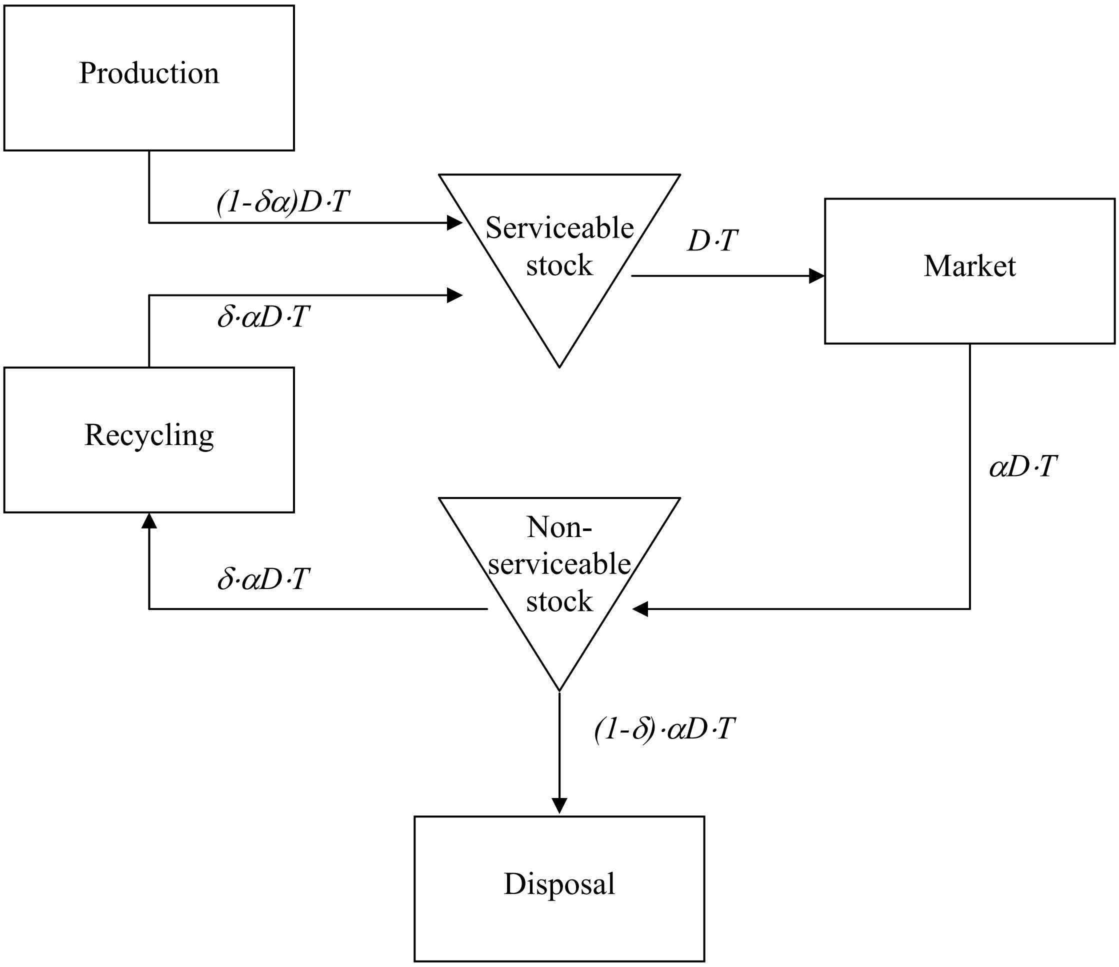
$$T_P^o(1,1)=\sqrt{\frac{2S_R}{D\cdot(h_s+h_n)(1-\gamma)}},\tag{15}$$

$$x_P^o(1,1)=\sqrt{2DS_R(h_s+h_n)(1-\gamma)}.\tag{16}$$

The total inventory cost function for all the cases is

$$C_I(\delta,\alpha)=\begin{cases}\sqrt{2DS_P\cdot h_s(1-\beta)} & \alpha\delta=0\\ \sqrt{2DS\cdot V(\delta,\alpha)} & 0<\alpha\delta<1.\\ \sqrt{2DS_R\cdot(h_s+h_n)(1-\gamma)} & \alpha\delta=1\end{cases}\tag{17}$$

Figure 3. The material flow in the model in a production and recycling cycle



5. Minimizing the inventory holding costs for the buyback and use rates

Before minimizing the inventory holding costs (17) we will prove a simple lemma.

Lemma 3: Let values *a, b, c* and *d* be positive. Then the following equality holds

$$\sqrt{(a+b)(c+d)}\geq\sqrt{ac}+\sqrt{bd}\ .$$

Proof. Let both sides of the inequality raise to the second power. Then

$$(a+b)(c+d)\geq ac+bd+2\sqrt{abcd}$$

and after simplifying

$$ad + bc \geq 2\sqrt{abcd}$$

and this inequality holds for all positive *a, b, c* and *d*, because $\left(\sqrt{ad} - \sqrt{bc}\right)^2 \geq 0$.

Let us apply this result to the mixed strategy:

$$\sqrt{2DS \cdot V(\alpha,\delta)} = \sqrt{2D(S_P + S_R) \cdot \left[(1-\alpha\delta)^2 h_s(1-\beta) + \alpha^2\delta^2 h_s(1-\gamma) + \alpha^2\delta^2 h_n\left(\frac{1}{\alpha} - \gamma\right)\right]}.$$

Let now

$$\begin{aligned} a &= 2DS_P \\ b &= 2DS_R \\ c &= (1-\alpha\delta)^2 h_s(1-\beta) \\ d &= \alpha^2\delta^2 h_s(1-\gamma) + \alpha^2\delta^2 h_n\left(\frac{1}{\alpha} - \gamma\right) \end{aligned}$$

Using the result of lemma 3 we have the following inequalities

$$\begin{aligned} &C_I(\alpha,\delta) \geq \sqrt{2DS_P \cdot (1-\alpha\delta)^2 h_s(1-\beta)} + \sqrt{2DS_R \cdot \left[\alpha^2\delta^2 h_s(1-\gamma) + \alpha^2\delta^2 h_n\left(\frac{1}{\alpha} - \gamma\right)\right]} = \\ &= (1-\alpha\delta)\sqrt{2DS_P \cdot h_s(1-\beta)} + \alpha\delta\sqrt{2DS_R \cdot \left[h_s(1-\gamma) + h_n\left(\frac{1}{\alpha} - \gamma\right)\right]} \geq \\ &\geq (1-\alpha\delta)\sqrt{2DS_P \cdot h_s(1-\beta)} + \alpha\delta\sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)} \end{aligned}$$

The last inequality holds because $\frac{1}{\alpha} \geq 1$. The last expression is a convex linear combination of the pure strategies, i.e. the recycling and production. The weights are the possible products of marginal use and buyback rates $\alpha\delta$ which is non-positive and not greater than one. This cost expression is always greater than the smaller of the costs of pure strategies:

$$\begin{aligned} &(1-\alpha\delta)\sqrt{2DS_P \cdot h_s(1-\beta)} + \alpha\delta\sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)} \geq \\ &\geq \min\left\{\sqrt{2DS_P \cdot h_s(1-\beta)};\ \sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)}\right\} \end{aligned}$$

By this last inequality the following statement is proved:

Theorem 1: The optimal inventory holding strategy in this production-recycling model is a pure strategy: either to produce to meet the demand ($\alpha^0 = \delta^0 = 0$) or to buy back and to recycle all used product without production ($\alpha^0 = \delta^0 = 1$).

Example 5. Let $D=200$, $\beta = \gamma = 2/3$, $S_P = 144$, $S_R = 72$, $h_s = 12$ and $h_n = 3$. Then the inventory holding costs of recycling is 379.473 and that of production 480. It is economical to recycle with buyback all used items.

Example 6. Let *D=200,* β *=11/13* γ *= 9/13,* S_P *=144,* S_R *=72,* h_s *= 6.5* and h_n *= 3*. Then the inventory holding costs of production is 240 and that of recycling 290.146. It is more effective to produce and not to recycle.

6. Minimizing the total lot-size related and lot-size independent costs

In this section we minimize the sum of the EOQ-related and EOQ independent costs. In this case the cost function is

$$C_T(\alpha,\delta) = C_I(\alpha,\delta) + C_N(\alpha,\delta)$$

where function $C_N(\alpha,\delta) = C_W \cdot (1-\delta)\alpha D + C_R \cdot \delta\alpha D + C_P \cdot (1-\delta\alpha)D + C_B \cdot \alpha D$ is the sum of the linear waste disposal, recycling, production and buyback costs. This cost function can be written as follows

$$C_T(\delta,\alpha) = \begin{cases} \sqrt{2DS_P \cdot h_s(1-\beta)} + DC_P & \alpha\delta = 0 \\ \sqrt{2DS \cdot V(\delta,\alpha)} + \delta\alpha \cdot D(C_R - C_P - C_W) + \alpha \cdot D(C_W + C_B) + DC_P & 0 < \alpha\delta < 1. \\ \sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)} + D(C_R + C_B) & \alpha\delta = 1 \end{cases}$$

The problem to be solved has the form

$$C_T(\delta,\alpha) \rightarrow \min$$

subject to

$$\delta \in [0,1], \quad \alpha \in [0,1].$$

In the last section we have seen that

$$C_I(\alpha,\delta) \geq (1-\alpha\delta)\sqrt{2DS_P \cdot h_s(1-\beta)} + \alpha\delta\sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)}$$

i.e. the inventory holding costs are not greater than the convex linear combination of the pure production and recycling strategies. The non-EOQ related costs can be approximated in the following way

$$C_N(\alpha,\delta) \geq (1-\delta\alpha)D \cdot C_P + \delta\alpha D \cdot (C_B + C_R).$$

To get this inequality, we have reduced the lot-size independent costs with the waste disposal costs $C_W \cdot (1-\delta)\alpha D$ and with costs of bought back but not recycled items $C_B \cdot (1-\delta)\alpha D$.

With these two approximations we can give a lower bound on the total cost function

$$C_T(\alpha,\delta) \geq (1-\alpha\delta)\left\{\sqrt{2DS_P \cdot h_s(1-\beta)} + D \cdot C_P\right\} + \alpha\delta\left\{\sqrt{2DS_R \cdot (h_s + h_n)(1-\gamma)} + D \cdot (C_B + C_R)\right\}.$$

The right-hand expression is again a convex linear combination of the pure strategies, therefore

$$\begin{aligned}&(1-\alpha\delta)\left\{\sqrt{2DS_P\cdot h_s(1-\beta)}+D\cdot C_P\right\}+\alpha\delta\left\{\sqrt{2DS_R\cdot(h_s+h_n)(1-\gamma)}+D\cdot(C_B+C_R)\right\}\geq\\&\min\left\{\sqrt{2DS_P\cdot h_s(1-\beta)}+D\cdot C_P,\sqrt{2DS_R\cdot(h_s+h_n)(1-\gamma)}+D\cdot(C_B+C_R)\right\}\end{aligned}.$$

This result proves the next

Theorem 2: The optimal production-recycling strategy for the total cost model is either buy-back all sold and used items ($\alpha^0 = \delta^0 = 1$) or production without buyback and recycling ($\alpha^0 = \delta^0 = 0$).

A similar result was shown by Richter [8] for another waste disposal model. In the case of linear waste disposal, production, recycling and buyback costs and free choice of buyback and recycling rates between 0 and 1 one of the pure strategies to buy back and recycle and to produce is optimal. The optimal pure strategy can be found by comparing the values $\sqrt{2DS_P\cdot h_s(1-\beta)}+D\cdot C_P$ and $\sqrt{2DS_R\cdot(h_s+h_n)(1-\gamma)}+D\cdot(C_B+C_R)$.

7. Conclusions and further research

In this paper we have investigated a production-recycling model. Minimizing the inventory holding costs it was shown that one of the pure strategies (to produce or to recycle all products) is optimal. A similar proposition can be made in case of a with lot-size independent costs generalized model. A similar result was obtained by Richter [8] for a waste disposal model with remanufacturing.

Probably these pure strategies are technologically not feasible and there will always exist some not returning used products which then can not be recycled. This kind of generalization of this basic model could be the introduction of an upper bound on the buyback rate which is strongly smaller than one. In such a case a mixed strategy would be economical comparing to the pure strategy "production".

We have assumed that there are only one production and recycling lot-sizes. In a general model the effect of the number of batches on the production-recycling could be investigated. How depends the number of the bathes on the buyback, is a question to be answered.

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